THE RECONSTRUCTION OF VIRTUAL CUNEIFORM FRAGMENTS IN AN ONLINE ENVIRONMENT

by

ANDREW WILLIAM LEWIS

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Ironbridge International Institute for Cultural Heritage
Digital Humanities Hub
College of Arts and Law
University of Birmingham
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ABSTRACT

Reducing the time spent by experts on the process of cuneiform fragment reconstruction means that more time can be spent on the translation and interpretation of the information that the cuneiform fragments contain. Modern computers and ancillary technologies such as 3D printing have the power to simplify the process of cuneiform reconstruction, and open up the field of reconstruction to non-experts through the use of virtual fragments and new reconstruction methods. In order for computers to be effective in this context, it is important to understand the current state of available technology, and to understand the behaviours and strategies of individuals attempting to reconstruct cuneiform fragments.

This thesis presents the results of experiments to determine the behaviours and actions of participants reconstructing cuneiform tablets in the real and virtual world, and then assesses tools developed specifically to facilitate the virtual reconstruction process. The thesis also explores the contemporary and historical state of relevant technologies. The results of experiments show several interesting behaviours and strategies that participants use when reconstructing cuneiform fragments. The experiments include an analysis of the ratio between rotation and movement that show a significant difference between the actions of successful and unsuccessful participants, and an unexpected behaviour that the majority of participants adopted to work with the largest fragments first. It was also observed that the areas of the virtual workspace used by successful participants was different from the areas used by unsuccessful participants. The work further contributes to the field of reconstruction through the development of appropriate tools that have been experimentally proved to dramatically increase the number of potential joins that an individual is able to make over period of time.

DEDICATION

This thesis is dedicated to my parents, who have offered constant, unwavering support throughout my entire academic career.

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Glossary of Terms

ABS
Acro Butyl Styrene. A hardwearing, flexible oil based plastic commonly used in 3D printing.

BDTNS
The Database of Neo-Sumerian Texts (BDTNS) is an online collection of cuneiform tablets developed at the Centro de Ciencias Humanas y Sociales of the Consejo Superior de Investigaciones Científicas (Madrid).

CDLI
The Cuneiform Digital Library Initiative.

CDFP
The Cuneiform Digital Forensic Project.

DOF
Degrees of Freedom. The number of independent components of motion required to describe the movement of an object.

FD
Field Dependence is a cognitive style that can be tested for with the GEFT. FD individuals are more susceptible to external influence in tasks.

FI
Field Independence is a cognitive style that can be tested for the with the GEFT. FI individuals are considered to have better geometric problem solving abilities and are less influenced by external sources when completing tasks.

FIFO
First In, First Out – A buffering system used in computers that operates like a queue, with the first item entering the queue being the first item to leave.

FDM
Fused Deposition Modelling. A method of 3D printing that fuses together filament or powder (usually plastic, but sometimes metal) using heat.

JSON
JavaScript Object Notation. A lightweight data-interchange format that is easy for humans and machines to read and generate.

Node.JS
A javascript based application server.

PEEK
Polyether ether ketone is a type of plastic sometimes used to build the hot end of 3D printers. The plastic is rigid and difficult to machine, but has a high melting point.

PLA
Poly Lactic Acid. A hard but brittle biodegradeable plastic commonly used in 3D printing as a filament.

ThreeJS
A Library for JavaScript that makes the process of creating and implementing 3D graphics and physics simulations less complicated.

NASA TLX
National Aeronautics and Space Administration Task Load Index. A test designed by NASA to measure the mental and physical load that performing a task causes.

GEFT
The Group Embedded Figures Test is a test designed to measure the cognitive style of individuals. The GEFT is easy to administer, and is the successor to the early rod and frame tests used to measure field independence/dependence.

CHAPTER 1: INTRODUCTION

1.1 Background

Cuneiform is an ancient logographic script originating in Mesopotamia, around the area of the Tigris-Euphrates river system. Cuneiform script can be easily distinguished by the characteristic wedge-shaped impressions that form the sub-elements of each symbol, and it is most frequently found on clay (or stone) tablets, seals, and markers from the ancient near east. The historical data contained within these clay tablets is diverse. Cuneiform is used to convey information on mathematics, law, medicine, contemporary events, shop inventories and orders, educational matters, royal decrees, and certificates of authenticity from traders in a number of different language.

Unfortunately, many of these tablets have been adversely affected by environmental and cultural factors and effective decipherment of the tablets is hampered by fragmentation. Some considerable effort is required to identify and join the fragments before the process of translation can be completed by scholars. This process of reconstruction is manual, and handling of the fragile tablet pieces requires special training. The fragility of these fragments, the methods of safe storage, and the geographical dispersion mean that the process of matching broken fragments is necessarily slow, with only a few experts available to search collections for matches.

It is reasonable to assume that the digitisation of tablets and the automation of all or part of the reconstruction process could improve the number of matches made in a given period of time, or at the very least free scholars from the arduous task of attempting to solve a widely bounded 3D puzzle by allowing non-experts to attempt reconstruction using virtual fragments.

This project attempts to answer several questions related to the cuneiform reconstruction problem. Firstly, the principal question of whether digital methods can effectively improve the current reconstruction process is considered, including the practicality and effectiveness of virtual environments for the reconstruction of cuneiform fragments. Once this is suitability has been established, the mechanisms behind the reconstruction process must be understood, with particular reference to reconstruction by virtual, manual, and automatic methods including crowdsourcing and automatic reconstruction. Answering these questions is only possible by adopting approaches that straddle multiple disciplines, and it is therefore unsurprising to discover that supervision support for this project is taken from two different colleges.

1.2 Contributions

Specific contributions made by this project arise from three principal areas:

The Photogrammetric analysis of cuneiform fragments, in which a novel method for the analysis of images in the CDLI database reveals the dimensions of cuneiform tablets and provides a template for the shape and size of complete tablets that can be used during the reconstruction process.

Findings arising from a study identifying the strategies and behaviours employed by participants in fragment reconstruction tasks in the physical and virtual world, which links successful task performance to certain behaviours and strategies.

The development of specialised tools and a novel framework that can significantly improve user performance in fragment reconstruction tasks in a virtual environment.

1.3 Research Questions

There are overarching issues regarding the current state of cuneiform reconstruction, on whether 3D capture and visualization present as a practical method for the preservation by record of cuneiform fragments, and whether the current state of technology can support automatic or manual reconstruction of cuneiform tablets in a meaningful way. These are nuanced questions that require a multifaceted answer with both technical and historical aspects. Firstly, the level of technology currently available must be explored, as must the historical methods for the recording and reconstruction of cuneiform fragments. With this historical understanding in mind, the current state of available technology was examined to ascertain whether it make the process of cuneiform reconstruction faster or easier in some way, and what potential barriers exist to the adoption of this new technology. Following on from this, the research sought to identify what strategies and behaviours people employ when carrying out fragment reconstruction tasks in the physical and virtual world. Finally tools and technologies that improve the performance of people during the fragment reconstruction process were tested, to assess their effectiveness.

Concisely expressed, the questions that this thesis addresses are:

1. Is 3D capture and visualization a practical method for the preservation by recording of cuneiform fragments, and does the current state of technology support automatic or manual reconstruction in a meaningful way?
2. What strategies and behaviours are employed during fragment reconstruction tasks in the real and virtual world?
3. Can virtual tools be used to increase the level of interaction between users and fragments the virtual environment?
4. Can virtual tools be used to increase the number of fragment joins that a user makes in the virtual environment?

1.4 Methodology

This project employs a combination of literature review, practical experimentation, and analysis using both quantitative and qualitative methods to answer the research questions outlined above.

The research process was iterative, beginning broadly with experiments to understand the geometry of cuneiform tablets, and investigations to determine the current state of technologies that may be used in the virtual reconstruction of cuneiform tablets. As research into these fields indicated that an appropriate automated reconstruction solution was unlikely, further research was directed towards solutions that might facilitate virtual reconstruction by humans. This included 3D printing and 3D scanning technology, and also experiments to build an understanding of the specific methods employed by humans during the reconstruction process. Practical experimentation was used to answer overarching questions about the effectiveness of new technologies for cuneiform reconstruction, and existing technologies were developed to a point where they were useful in the context of cuneiform reconstruction.

Early experiments involving the photogrammetric analysis of cuneiform tablets relied heavily on computation with digital images to yield results, while experiments with laser scanning and printing required a more hands-on approach to research and experimentation. Additional experiments were designed once the results of the early experiments were processed. These experiments were designed with two distinct goals in mind. Firstly, to understand the task of cuneiform reconstruction in the real and virtual world by the observation of participants, so that new tools could be developed to facilitate the process of reconstruction. Secondly, to implement and assess the effectiveness the tools designed as a result of the earlier experiments. These later experiments used a combination of techniques including contextual interviews and participatory design, and also the quantitative analysis of detailed computer logs and user performance. Standard questionnaires like the NASA TLX (Task Load indeX) and SUS (System Usability Scale) were also used to garner additional information about participants and their performance.

1.5 Publications

Lewis A & Ch'ng E (2012) *A Photogrammetric Analysis of Cuneiform Tablets for the purpose of Digital Reconstruction*, International Journal of Cultural Heritage in the Digital Era, EuroMED Suppl. 1 (1), p 49-53.

Lewis A, Woolley S, Ch'ng E, Gehlken E. (2014) *Observed Methods of Cuneiform Tablet Reconstruction in Virtual and Real World Environments*, Journal of Archaeological Science, vol 53, p 156-165

Ch'ng E, Lewis A, Gehlken E, Woolley S. (2013) *A Theoretical Framework for Stigmergetic Reconstruction of Ancient Text. In Visual Heritage in the Digital Age*, Springer Cultural Computing Series. p 43

Ch'ng, E., Woolley, S. I., Hernandez-Munoz, L., Collins, T., Lewis, A., & Gehlken, E. (2014, December). *The development of a collaborative virtual environment for 3D reconstruction of cuneiform tablets*. In Virtual Systems & Multimedia (VSMM), 2014 International Conference on. p 35-42. IEEE.

Collins T, Woolley S, Gehlken E, Lewis A, Hernandez Munoz L. (In Preparation) *A Photogrammetric Scanning System for the Low-Cost 3D Capture of Archaeological Artefacts*. ACM Digital Heritage

Collins T, Woolley S, Gehlken E, Lewis A, Hernandez Munoz L, Ch'ng E & Ghelken E. (2014) *Computer-Assisted Reconstruction of Virtual Fragmented Cuneiform Tablets*. In Virtual Systems & Multimedia (VSMM), 2014 International Conference on. p 70-77. IEEE

CHAPTER 2: LITERATURE REVIEW I

Historical Aspects of Cuneiform Reconstruction and Related Technologies

In chapter 1, the foundation and overarching methodology for the project was explored, outlining the need to understand the history of cuneiform reconstruction and the adoption of technology into the field. This chapter explores the historical approaches to cuneiform reconstruction, and the origins of the cuneiform reconstruction problem. This chapter also looks at some of technologies that were suitable for recording and visualising cuneiform fragments, and investigates why these were not always adopted.

2.1 Cuneiform

Cuneiform tablets vary in size from approximately an inch to (in some cases) over a foot in length(Anderson & Levoy, 2002). Despite the implications of their taxonomy, the term 'tablet' may refer to one of a number of shapes. The most notable deviations from the expected form of a clay tablet can be found in collections of seals and stamps, which may be cylindrical or even spherical in their geometries. Other 'tablets' may be conical, cubic, prismatic, or rectangular in appearance (Walker, 1987).

The intellectual diversity of the tablet contents is matched only by the considerable variation in their physical structure and condition. Depending on the contents of the inscription, a clay tablet might have been sun dried or kiln fired to preserve it. Unfortunately for modern scholars, sun dried tablets are chemically unstable, and are susceptible to damage from a multitude of sources. Aside from the obvious risk of water or shock damage, some types of clay contain mineral salts that can crystallize on the surface of tablets over many years. If left untreated, these crystals can cause irreparable damage to the inscribed surfaces of a tablet (Organ, 1961). Even fired tablets are not immune to damage, and special handling procedures are necessary to prevent damage to the fragile artefacts(The British Museum, 2011).

Common sense dictates that these tablets must be preserved for future generations. However, the results of 18th century experimental preservation techniques were occasionally disastrous, and could result in the complete destruction of the tablet under examination. In other cases, the careless storage or handling of tablets after preservation lead to additional damage (Budge, 1925).

2.2 The Fragmentation and Dispersal of Cuneiform text between the 17th to 21th century

The susceptibility of clay tablets to fracture and fragmentation presents a problem that is exacerbated by geographical dispersal. The Amarna letters present a perfect Figure of this problem. Originally a homogeneous body of cuneiform tablets, the Amarna collection is now divided across no less than four different museums. Tablets from the Amarna collection are housed in the British Museum (London), the Ashmolean Museum (Oxford), the Vorderasiatisches Museum (Berlin), and the Egyptian Museum (Cairo). In order to make a detailed analysis of fragments within the collection, it is necessary to travel several thousand miles and requires the cooperation and support of staff in multiple countries(Izre'el, 1997).

How can it be that the ancient knowledge of Mesopotamia has become scattered so thoroughly across the globe? The story behind the fragmentation of the cuneiform archives begins at the apogee of the Italian renaissance, when European interest in the ancient world was waxing (Saggs, 2000).

Biblical references to Mesopotamia helped ensure that the region surrounding the great rivers figured in the itinerary of many religious travellers, and the existence of cuneiform markings in the near east was recorded by western visitors as early as the 15th century(Schmandt-Besserat, 1992). The Renaissance period traveller Pietro della Valle not only provided a detailed description of the ruins of Babylon, but returned home in the early part of the 17th century with a collection of inscribed bricks taken from the mound of Tall al Muqayyar(Kramer, 1963). At that time, there was very little chance that western scholars could decipher the mysterious markings found on the clay bricks, since so few examples were available for analysis. The first steps toward a meaningful analysis of cuneiform were taken by a Danish surveyor and mathematician named Carsten Niebuhr. During the course of his expedition into Mesopotamia, Neibuhr made extensive notes and Figures of the inscribed texts at the Great Rock of Behistun (Kramer, 1963). These Figures were presented in the second volume of Neibuhr's “Reisebeschreibung nach Arabien und anderen umliegenden Ländern” (Niebuhr, 1774) .

The accurate reproductions of the inscribed text at Behistun finally provided scholars with the information they needed to begin decoding the ancient languages that it represented, but progress on the translation was slow. It was not until the expedition of Sir Henry Rawlinson in 1835 that the translation of cuneiform started to pick up speed.

As western interest in cuneiform and the ancient near east grew, the export of eastern antiquities began in earnest. Contemporary evidence suggests that the early excavations were far from scientific, as is explained by A.H. Sayce in “The Archaeology of Cuneiform Inscriptions”(Sayce, 1908):

> *“The excavations controlled by the British Museum have, I am sorry to say, been for the most part destructive rather than scientific; such objects as were wanted by the Museum were alone sought after; little or no record has been kept of their discovery, and they have been mixed with objects bought from natives, of whose origin nothing was known. At one spot, Carchemish, the old Hittite capital, which, though not strictly in Assyria, formed part of the Assyrian Empire, and was the seat of an Assyrian governor, the so-called excavations conducted by the Museum in 1880 were simply a scandal, which Dr. Hayes Ward, who visited the spot shortly afterwards, has characterized as "wicked." The archaeological evidence there, which would have thrown so much light on the Hittite problem, has been irretrievably lost.”*

Poor archaeological practice was the least of the problems faced by those that sought to excavate the ruins of Mesopotamia. Dealers and officials realized that there was money to be made from the sale of antiquities to the west, and they began to make excavations of their own. Before long, the museums of the time had reduced their own excavations to a minimum, and were simply buying cuneiform tablets from the local dealers(Budge, 1925). Budge describes quite neatly the situation faced by contemporary archaeologists:

> *“As soon as the dealers and officials in Baghdad knew that Rassam was out of the country they began to make excavations on their own account. They employed the workmen who had been employed by Rassam; and in a very short time the Jews of Hillah, working in collusion with the Jews and Armenians of Baghdad, began to export large collections of tablets and other antiquities to London and America.*

> *The British Museum bought several collections, and as there was keen competition in Paris and America prices began to soar, and in a short time contract tablets of Nebuchadnezzar II, for which the finders were paid five piastres each in Baghdad, were fetching £4. each in London. It was, of course, quite hopeless to stop the trade in anticas at Baghdad; and as long as Museums found it cheaper to buy tablets than to dig for them, naturally their Directors bought. But presently Rawlinson and others found out, by reading the tablets which the British Museum bought in the open market, that several of them came from the sites on which Rassam had worked and which the agents appointed by him were being paid salaries to watch. Moreover, information reached the Museum from Prof. Sachau and others that German agents of the Berlin Museum had travelled via Mosul to Baghdad, and had bought collections of Babylonian tablets from the watchmen paid by the Trustees."*

So began the fragmentation of the ancient knowledge of the near east. Museums, dealers, local officials, and even governments were in direct competition with each other for political, financial, and personal reasons (Budge, 1925; Nemet-Nejat, 1998) . Reports from the period indicate that collections of tablets numbering in the tens of thousands were being exported to Europe and America by any available means, and little could be done to stem the illicit trade:

> *"On many of the sites men were digging for tablets openly by daylight; no watchmen were there, and had they been there, they could not have prevented digging. At every place I visited I purchased good tablets at the rate of from three to five piastres each. The Turkish governor of Hillah told me that Abu Habbah and neighbouring mounds were situated on lands that were the personal property of the Sultan 'Abd-al-Hamid Khan, and that His Majesty and the Baghdad Government greatly resented the appointment of watchmen by Rassam on the Crown Domains."(Budge, 1925)*

The wholesale disinterment of cuneiform tablets and other relics continued through the beginning of the 20th century. At the end of the first world war, the British were awarded a temporary mandate over Iraq by the league of nations. The mandate was set in effect until Iraq was considered ready for independence. It was during this period when a department of antiquities was created in Iraq, and antiquities laws were put into place to reduce the cultural losses incurred by frequent international excavations (Nemet-Nejat, 1998).

Further laws were passed in 1958, and the UNESCO Convention on the Means of Prohibiting and Preventing the Illicit Import, Export and Transfer of Ownership of Cultural Property, was passed in November 1970, further retarding the illicit trade in cultural antiquities.

In more recent years, the conflicts in Iraq have had a marked effect on the state of archaeological sites of the Tigris-Euphrates area. The 2011 UNESCO publication “The Fight Against The Illicit Trafficking Of Cultural Objects” (UNESCO, 2011) provides a tally of loss and recovery for anyone interested in the conservation of antiquities:

> *“During the 1991 Gulf War, 3,000 known antiquities disappeared in Iraq. It’s estimated that many thousands of other non inventoried objects have been removed from ancient sites. At the same time, the number of artefacts for sale in London and New York increased in a marked measure.*
>
> *The spoliation of the Sennacherib Palace at Nineveh is particularly documented: the robbers broke bas-reliefs to carry them more easily.*
>
> *During the operations against Saddam Hussein, around 15,000 artefacts were robbed from the Baghdad Museum. Seven thousand were recovered: 2,000 in the USA, 250 in Switzerland, 100 by Italian Carabinieri, 2,000 were stopped in Jordan, others in Beirut and Switzerland while in transit to New York. But the statue of Entemena, King of Lagash (2,450 BC) has not been recovered to date.*
>
> *The Magistrate of the State of Delaware (USA) has restituted 25 cuneiform slabs to Iraq, from where they had been robbed. They were found in July 2010 by an art dealer in California.”*

The document contains further details of antiquity theft and restitution in Iraq, indicating that the problem of fragmentation in the cultural heritage of Iraq is as much an issue today as it was 150 years ago – And, with such a turbulent and colourful history of excavation, it is no surprise that fragments of cuneiform tablets can be found scattered across the globe.

2.3 Artefacts as an Interface to Data

The accurate recording of an artefact is important for a number of reasons. Not least of these reasons is apparent in the wise guidance of Sir William Mathew Flinders Petrie; to record everything in as much detail as possible. This is a (now commonly held) sentiment shared by Sayce, who comments that “Scientific excavation means, before all things else, careful observation and record of every piece of pottery, however apparently worthless, which the excavator disinters.” (Sayce 1908). While Petrie and Sayce were speaking within the context of archaeological excavation (which is in some cases by necessity a destructive process), it can also be argued that there is an implicit duty to record the characteristics of already excavated objects as fully as possible, to protect against their loss through any means including theft, war, or natural disaster.

From a computational or HCI standpoint, we can regard excavated and in-situ artefacts primary interfaces to historical data. These are physical objects that can be accessed and manipulated in a variety of ways to extract data from them. It is in the interest of the heritage community that the data within the object should be protected against loss by any means possible. The repercussions of loss or damage to the object as an interface can be greatly mitigated if the data that behind the interface can still be accessed and interpreted in the absence of the original object.

Modern science can provide a huge amount of information about an artifact's history through the methods of carbon dating(Taylor, Bar-Yosef, & Renfrew, 2014), microwear analysis using laser scanning conifocal microscopy (Stemp et al. 2013), archeomagnetism (Carvallo & Dunlop 2001), and spectrometry. It is possible that metrological data captured in the present day may one day be examined with algorithms and technology that are currently unavailable. It is quite possible that advances in scanning and visualization technology will be able to manipulate and enhance the information extracted from current scan data, and so every effort must be made to facilitate future examination by providing as much data as is possible about the surface and structure of cuneiform fragments.

2.4 Cataloguing Cuneiform

With the potential for loss and damage, the need for effective recording techniques for cuneiform fragments is clear. Beyond the recording of individual tablets, there also exists a need for adequate cataloguing and retrieval mechanisms for cuneiform fragments. The range and quantity of tablets collected during the 19th and early 20th century meant that the need for proper referencing and documentation was paramount. Unfortunately, the pioneering scholars of cuneiform studies had limited tools for the recording of finds, and individual scholars familiarity with the collections led to some delay in the creation of detailed catalogues (Budge, 1925).

At the British Museum, the Kuyunjik collection represents a clear example of the delays to the effective cataloguing of finds. Although excavated in the 1850s, many of the Kuyunjik tablets were left uncatalogued for several years. It was only the intervention of Samuel Birch and Sir Peter Le Page Renouf (both serving as Keeper of Oriental Antiquities at the British Museum) that lead to the eventual development of a catalogue of the cuneiform artefacts.

The matter of cataloguing the thousands of items in the department of Oriental Antiquities was not a simple one. Finds from different excavations had been mixed together over time, and there was (at that time) little to distinguish finds from the Kuyunjik mound at Ninneveh with those from other sites (Reade, 1986). Birch was no expert in the translation of Cuneiform text, and despite raising the issue of a catalogue several times, it would be over 30 years before a beginning was made by Birch's replacement (Sir Peter le Page Renouf).

Complete catalogues of the Kuyunjik collection were produced between 1889 and 1896, and provide a 2500 page record of the of 22,220 tablets (Budge, 1925). The tablet descriptions in the Kuyunjik catalogue are detailed, but there are no Figures of physical shape for the tablets fragments, and only basic measurements of the physical size are included. While this is acceptable for the purposes of translation, it does not facilitate easy reconstruction of disconnected fragments. The following extract from the first edition of the catalogue (published in 1889) shows the limitations of the text only format:

> *"Fragment out of the middle of a terracotta prismoid, 3 in. high, one side at least 2 in. Remains of two columns, with 19 and 10 clearly written Assyrian lines. The lines of Column I are mutilated at their beginnings, and of Column II, only very short beginnings of lines are preserved. Parts of an inscription of Sardanapallos. What is left of the text corresponds to K. 2732 (q.v.), Column III, lines 22-45; and Column IV, lines 62-71. [K. 1732]"*

The omission of a pictorial record of the archives is understandable, since the space required for images of each tablet would have increased the size of the complete publication by over 10000 pages. The additional printing costs and preparation time of so large a document could not have been practical at the time of production. The issues associated with the visualization of cuneiform tablets was addressed in the Journal of the Photographic Society of London(Diamond, 1866), where it was noted that:

> *"It is a boon of enormous value to be able in any instance to eliminate that fruitful source of error, the fallibility of the observer. Photography is never imaginative, and is never in any danger of arranging its records by the light of a preconceived theory."*

And, with specific reference to cuneiform:

> *"In matters of such delicate rendering as Egyptian hieroglyphics, Sinaitic carvings, Cuneiform inscriptions, tho question whether this w that mark upon the weather-worn stone shall be recorded as the remains of a line or a dot, or shall be overlooked as a defect produced by age, will be decided, in the work even of the most conscientious draughtsman, by the interpretation which he places upon the symbols he is recording. Such inaccuracy in the observer generates a corresponding inaccuracy in the student who generalizes from his observations. The student knows how the observations are taken, and justly looks upon them as all more or less arbitrary and conjectural; he is ready enough, therefore, whenever he is hopelessly at a loss, to evade the difficulty by audacious emendation. After all, the error may have been only the copyist's doing, and the true original may be in favour of his view."*

In discussing Sir Henry Rawling's publication of selected tablets, Budge reflects on the inaccuracies introduced by the lithographers employed to illustrate the work and justifies the decision to use photo-lithographs (rather than handmade lithographs) in the 1896 publication of "Cuneiform Texts in the British Museum":

> *"It had been found that when the lithographer drew the inscriptions on the stones from the copies supplied to him, he made many mistakes, and that some of these escaped, quite naturally, the notice of the editor. To avoid this, it was decided to transfer the copies of the texts to the stones by means of photo-lithography, and so one fruitful source of mistakes would be removed." (Budge, 1925)*

The advantages of photography over other methods of illustration seem clear, but it must be remembered that in 1842 (when WH Fox Talbot demonstrated benefits of the photographic process to the trustees of the British Museum), the cost of an individual photographic plate (as shown in the financial accounts of Antoine Claudet's studio off Adelaide Street, London)(Wood, 1979) was approximately 2s 6d. In 1864, some 10 years after Roger Fenton photographed over 8000 items of the Kuyunjik collection, the cost of photographic consumables would still make any large scale attempt at a published visual catalogue prohibitively expensive.

By 1896, it was still only practicable to produce sets of the most important fragments from the cuneiform collections using photo-lithographic Figures. The cost of materials were still a limiting factor in the production of cuneiform archives, and it has been stated in literature from the period that the sale price of many cuneiform catalogues were calculated to cover little more than the cost of printing (Budge 1925). Issues with the cost of photographic and lithographic reproduction in cuneiform catalogues persisted until the advent of the digital camera and scanner, whereby new recording techniques could be employed to record cuneiform tablets electronically (Woolley et al., 2002).

However, the introduction of digital capture and storage solutions are not a panacea for the cataloguing and curation of cuneiform, or indeed in the wider contexts of heritage and preservation. Richards et al. (2013) note that there has been a tremendous growth in the use of data, and in particular 3D data, in archaeology. This data may be used for digital preservation or monitoring, and as such it is important that the data is preserved in a way that facilitates reuse and reinterpretation. As Johnson et al. (2014) state, there is at the most fundamental level an issue of scale that must be addressed. The sheer volume of records being produced in digital format present a number of technical and procedural difficulties. Processes of backup, migration, and integrity checking become computationally expensive at scale, and human oriented tasks like file sensitivity reviews, may be completely impractical for very large datasets(McDonald, MacDonald, Ounis, & Gollins, 2014). From the evidence of these papers, a more pragmatic approach to digital preservation is required, and the concept of parsimonious preservation (Gollins, 2009) may provide the solution. Beyond issues of digital scale there are many other issues that present barriers to the long term preservation of cuneiform by digital recording. As Lunt et al. (2013) state, the ideal for archival storage is to be able to store an artefact and then forget about it, knowing that it will be available when we wish do access it in the future. In reality, the ephemeral nature of digital data means that the longevity of digital archives depends on a process of constant maintenance. The average lifespan of digital media is finite, and ranges between a few years in the case of magnetic media to a few decades for optical media. In order to maintain digital data, there must be a process by which the integrity of the stored data can be maintained, and this process is not free. At a higher level, Rothenberg (1995) raises the issue of obsolescence in digital preservation. Storage of digital data is useless if the method of recall is no longer understood. This sentiment is echoed by Delve et al. (2015), who list the input and extraction of data as major challenges to digital archiving, along with standardization of data formats and differences in legal directives and archival practices that may vary between countries. Gollins (2009) also considers this issue, noting that the ability to extract data in it's complete form at the end of the life of a proposed system is a capability that must be developed, and also adds that digital preservation is susceptible to attack by computer viruses or “infections”.

These limitations are not insurmountable, and the process of digital storage does offer some benefits over the traditional storage methods. In computerised databases like those of the Cuneiform Digital Library Initiative (CDLI) (CDLI, 2002), multiple direct scans of cuneiform tablets can be reproduced and searched virtually. The costs of print production are no longer a factor, and the physical space required to store an index of thousands of fragments is much smaller. The advent of the internet has provided cataloguers and academics with a globally accessible network free from the constraints of geography. The normal costs associated with print production have been radically deflated (Malakoff, 2003), and the availability of 'off-the-shelf' solutions like Sinleqiunnini can provide an instant solution to the problems associated with cataloguing a cuneiform collection.

Projects like the Cuneiform Digital Palaeography Project (Woolley et al., 2004) at Birmingham University have taken advantage of these digital advances in much the same way that the early pioneers of Assyrilogical cataloguing made use of new photo-lithographs and stereoviews. The BDTNS Database of Neo-Sumerian Texts (BDTNS 2015), funded by Consejo Superior de Investigaciones Científicas in Madrid provides another example modern digital resources, with a virtual collection of over 90000 administrative tablets all held together in one virtual database. The notable efforts of the CDLI at UCLA have shifted the cataloguing of cuneiform tablets into a global concern. The CDLI archives contain information and images on many of the worlds collections, using a standardized database that can be accessed remotely or downloaded locally in a populated or unpopulated form. Photographic records are mixed with line-art representations of tablets to provide a well populated visual record of collections.

2.5 Challenges to Reconstruction

Despite the advances made in the recording and cataloguing of cuneiform tablets, the processes employed to rebuild them still relies on glue and putty, with manual matching of fragments from catalogues or individual collections in the real world.

The reconstruction process can be hindered by the fragility and inaccessibility of the original fragments, and inadequate information about the size and shape of fragments within catalogues can make finding information difficult in some collections. Most catalogue data associated with cuneiform tablets concerns the content of the text, and not the physical appearance of the tablet. Where pictorial records exist, there are numerous hindrances to the proper recognition of a fragment. Images frequently lack of scale information, which is valuable in the determination of a fragment's physical dimensions. Where scale information is provided in a catalogue, the units of measurement may be omitted, and the numbers provided may be a product of human approximation rather than a scientific measurement. In cases where line drawing is employed, the human element can introduce multiple sources of error. Even photographic representation does not guarantee an error free representation of a cuneiform fragments. Camera orientation, fragment position, and lighting can all affect the clarity and apparent geometry of the object (Hameeuw & Willems, 2011). Close cropping, macro photography, and harsh lighting may improve the legibility of cuneiform inscriptions, but can also mean that the edge profile of a fragment can be lost completely. In these cases, the possibility of finding a match between separated fragments must rely on the translation of the content than on the physical characteristics of the fragments.

Currently, the only way of proving the correctness of a potential match between fragments is to physically join the pieces together in the real world. Given that two fragments may conceivably be on different continents, the delays in the matching process can be considerable. Even when large numbers of fragments are geographically collocated, the time required to discover matches can be daunting. Estimates from the University of Heidelberg show that at least 20 years will be required to reconstruct their collection of 20000 fragments into complete tablets, and simple mathematical analysis as stated by Ch’ng et al. (2013) seems to confirm this estimate.

2.6 Historical Capture of 3D Data

Having defined a need for accuracy in a 3D record, the practical issues of data acquisition must be discussed. While it is tempting to think of 3D scanning technology as being a recent innovation, the fact is that techniques for non-contact 3D capture and reproduction have been in existence for over a hundred years. Perhaps the most famous and popular method for 3D imaging in the last century is the stereogram (see Figure 1). The simple process of binocular capture of images that allows for the recovery of image depth when placed in an appropriate viewer. There even exist some examples of stereograms that depict inscriptions and artefacts from the near east circa 1900. While these early 3D representations are impressive, they do not allow for the recovery of the entire object in 3D, as the viewpoint is fixed and cannot be changed.

Figure 1: A stereogram from 1904, showing hieroglyphic inscriptions at Sehel. The stereogram is an early example of the use of 3D to record inscriptions. (Underwood & Underwood, 1904)

Other technologies for 3D scanning and even 3D printing have been in existence for an even longer time. In 1859, François Willème developed a technique which he referred to as “mechanical sculpture” (Gall, 1997), a process of producing sculptures using a series of 24 photographic profiles which could be projected onto a frosted glass sheet and traced with a pantograph and quickly mark sheets of wood for cutting. The wooden sheets were then cut and assembled to provide both a positive and negative representation of the source object. In later versions, the pantograph was modified to hone clay blanks into shape using a knife.

The rising popularity of the Photosculpture in the 19th century (see Figure 2, Figure 3) led to several developments in the process, although these mainly dealt with streamlining the manufacture of the end sculpture. A 1904 patent by Baese and another by Monteal in 1922 dealt with the use of plastic instead of clay for sculpture and for bas relief. The projection techniques utilised by François Willème could have been used to enlarge and copy small objects, although there is no evidence to support this ever happened. It is also unlikely that the system would have been able to detect sufficient surface detail to record cuneiform fragments in greater detail than a single photograph. Since the Photosculpture system relies on the profile of an object, the tiny cuneiform indentations on the surface of a tablet would be lost.

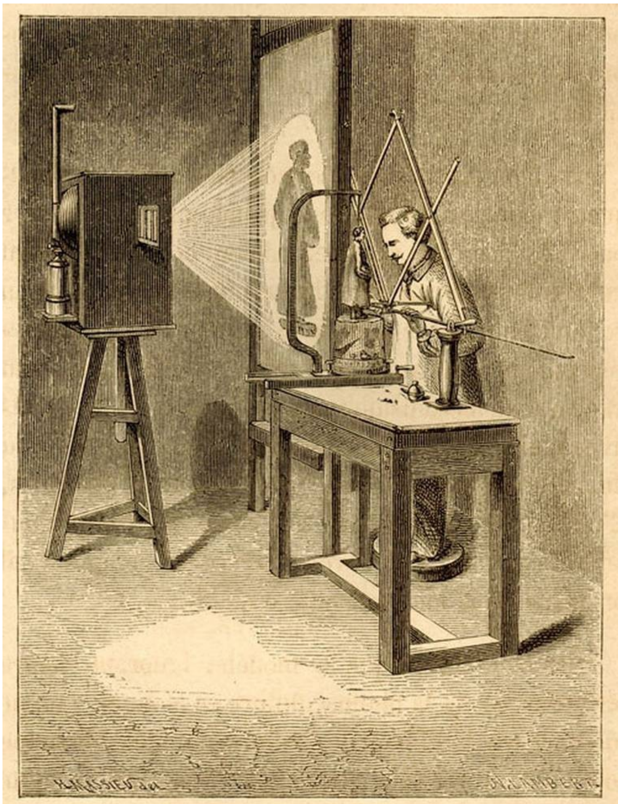

Figure 2: Lithograph illustrating thepantograph based portion François Willème's Photo Sculpture process. The photographic profile is projected onto frosted glass, and reproduced in clay. (Massieu, 1860)

Figure 3: These images show photographic output from some of the cameras used in the Photo Sculpture process. Since only the edge profile information is used, there are limitations to the detail which can be recovered using this method. (Willème, 1865a, 1865b)

It was not until 1935 that development of the photographic techniques more appropriate to the recovery of the fine detail were considered. Morioka (1935) describes the use of multiple lines projected across the surface of an object to capture surface deformations, and in 1939, a system very similar in operation to a contemporary laser line scanner was demonstrated by Marcus Adams (see Figure 4). Adams' system uses a single projected light and a revolving turntable to capture the line profile. With further modification, the system could undoubtedly have been used to record and reproduce cuneiform, although this application was not considered and the advent of the Second World War puts an end to the development of the photo sculpture process for several decades.

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Figure 4: This series of still images from Photo Sculpture (British Pathé, 1939) show the machinery and process used to 3D scan and manufacture a bust. This process was used in by Marcus Adams in 1939.

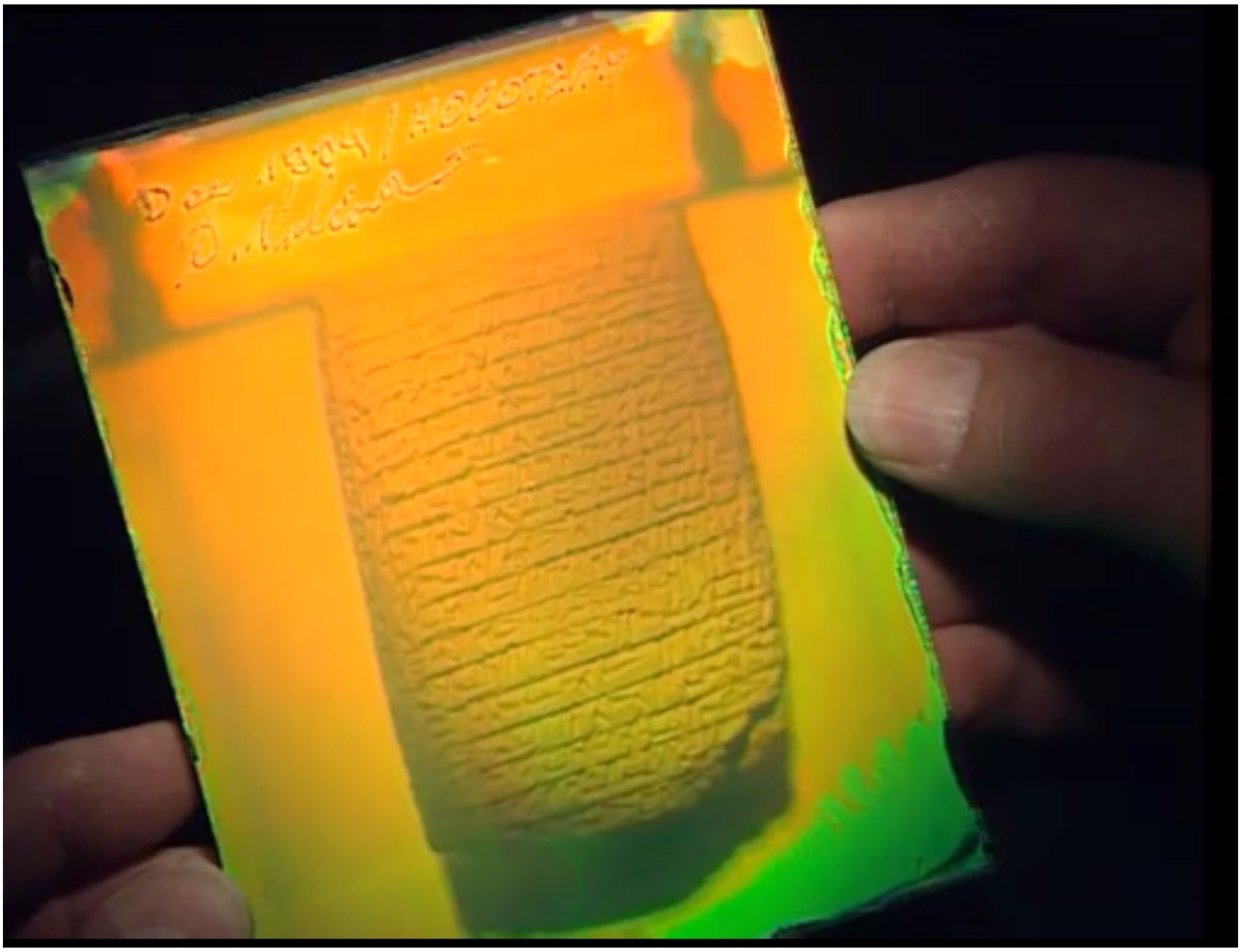


Figure 5: Example of a cuneiform tablet recorded using holographic technology, taken from DW Germany (1998).

More recently, the process of holography has been used to record and visualise the surface of cuneiform tablets (Roshop 1997; DW Germany 1998), as shown in Figure 5. The holographic field of view is still fixed to a narrow range, but it is less restrictive than the stereographic representations of inscribed texts from the early part of the 20th century.

2.7 Summary

This chapter has explored some of the methods that could be used to record and reconstruct cuneiform fragments, and looked at why these methods were not always widely adopted. It appears that the principle reasons for not using a particular technology was cost of materials and scale of work required to undertake the task of recording. Photography is a perfect example of this, with the high cost of photographic plates, and the physical space required to store or print the resulting photographs in volumes would have been enormous. Conversely, in the modern age, the costs of modern recording are bound to the digital curation and storage of data, rather than the provision of the raw materials to create the data itself. Creation of data has become cost effective, but the effective curation and storage of that data can present a constant financial drain.

CHAPTER 3: LITERATURE REVIEW II

Contemporary Technologies for the Recording and Reconstruction of Cuneiform Fragments

The previous chapter introduced the history of cuneiform and revealed how issues of cost and material availability affected the uptake of new technologies. This chapter explores contemporary methods related to the process of recording and reconstruction of virtual cuneiform fragments. This includes research into the areas of manual grasping, mental rotation, and 3D scanning and visualisation technologies.

3.1 3D Scanning

Some objects lend themselves readily to the process of 3D scanning, while others can present a considerable problem to certain types of 3D scanner. Reflective, absorptive, and dispersive surfaces present a particular problem for 3D laser scanners. The advantages and shortcomings of laser scanning technology are well reported by Hahn et al. (2007), and Chen et al. (2008), and have also been anecdotally expressed by those familiar with 3D laser scanning in the field. There are many cases where coherent laser light is affected by an object in such a way that it cannot be detected by the optical sensors, and scans of dark or reflective objects can be corrupt and unusable.

Cuneiform fragments (like most real world objects) require multiple scans to reproduce them in their entirety. Each scan must be taken from a different angle, so that all surfaces of the tablet can be recovered in 3D. It is not unusual for the surface of a tablet fragment to have a firing pattern or patina that varies in tone from black to light gray or orange. With a laser scanner, these deviations in surface colour can leave significant holes in captured data, and make the registration (merging) of multiple scans very difficult. When unusable scan data is encountered, a human operator must decide whether to either leave the hole in the data, try to rescan the area with different settings, or let the computer fill in the hole using a specialized algorithm. Leaving the hole will mean that data is missing from the final model. Nothing can be recovered from that area in the future, because the information is not recorded. Rescanning the area may be possible, but matching disparate laser scans automatically is not 100% accurate, and the process of manual or approximate matching must be used to align the scans.

The traditional method used to overcome the problem of missing data in industrial models involves the pre-application of a non-reactive powder or water soluble spray to mask difficult areas. Within the context of the heritage community, the application of such a chemical masking agent could irreparably harm a unique artefact. In order to scan difficult objects, an alternative to traditional laser scanning may need to be used.

Thankfully, laser scanners are not the only non-contact technology available for the capture of 3D objects. Structured light and photogrammetric scanners are now relatively commonplace, and can offer several advantages over laser scanning. Photogrammetric approaches to scanning like 123Catch (Autodesk 2015) and VisualSFM (Wu 2015), have gained popularity in recent years, although the accuracy of these systems is ultimately lower than close-range photogrammetry, laser based, or structured light scanning systems. (Chandler & Fryer, 2011).

Reflectance Transformation Imaging has been shown to be an effective choice for 3D capture of surface details and ancient inscriptions (Hameeuw & Willems 2013; Palma et al. 2010). The RTI system is fast, however, some studies indicate models created using RTI data can be less accurate than those created by other methods (Macdonald, 2004). RTI scanners usually employ an SLR camera in a hemispherical rig that is populated by fixed lights with a known position. Triggering the lights in sequence and photographing the effect on the fragment generates an interactive lighting model that can be adjusted to view the surface of a fragment. Although RTI was primarily envisioned as a 2D process, RTI images can be used to generate a 3D surface map. The principal issues associated with using RTI for 3D model generation are described by Macdonald, (2004), and it is shown that while the dome scanner presents an excellent method for visualisation of fragments with variable lighting conditions, the quality of the 3D model generated from RTI images is less accurate than other methods.

Photogrammetry using Autodesk's 123D-Catch or VisualSFM (Visual Structure from Motion System) are also a popular contenders for 3D scanning without lasers, but practical experimentation with small objects has shown that the time taken to capture a fragments and the low level of detail captured by the system prohibit the widespread use of this capture method for cuneiform fragments. Other examinations of the 123D-Catch system have shown that the resulting models are of lower accuracy than other methods, and are prone to distortion in some circumstances (Chandler & Fryer, 2011).

Techniques like 3D scanning and photogrammetry can provide accurate geometric data that can be manipulated in a virtual environment. It is even possible for a computer to assist a human in the matching process by providing a list of potential matches from a database of several thousand fragments. Research indicates that the field of virtual reconstruction is constantly improving the automated techniques of computer assisted reconstruction. Examples of automatic reconstruction can be seen with skull fragments in the fields of bioarcheology, palaeoanthropology, and skeletal biology (Gunz, Mitteroecker, Neubauer, Weber, & Bookstein, 2009; Kuzminsky & Gardiner, 2012), and also with pot and plasterwork in the fields of pot and fresco reconstruction (Brown et al., 2010; Karasik & Smilansky, 2008; Papaioannou, Karabassi, & Theoharis, 2002; Wong, Wu, & Gibbons, 2005). The wider academic community provides many examples where an increased understanding of a subject has resulted from the analysis of 3D data. The in-situ analysis of engravings in archaeological sites (Güth, 2012), the analysis and reconstruction of coins and coin fragments in numismatics (S Zambanini, M Kampel, & M Schlapke, 2008; Sebastian Zambanini, Schlapke, & Kampel, 2009), and the capture of graffiti on Roman pottery (Montani, Sapin, Sylvestre, & Marquis, 2012) are representative cases. More generally, the application of techniques for the automatic recording and illustration of artefacts (Gilboa, Tal, Shimshoni, & Kolomenkin, 2013) could be applied to 3D cuneiform models, and used to streamline the process of documentation while removing one potential source of recording error. More specific techniques for the reconstruction of cuneiform tablets have been made in Ch’ng et al. (2013) and Lewis & Ch’ng

(2012), which include the analysis of the complete tablet size as a template for fragment reconstruction, and the use of stigmergy as a model for interaction between users.

This approach to reconstruction is not without problems. There are issues regarding the efficacy of automatic reconstruction algorithms, the ability of a virtual systems to visualize scanned data effectively, and the usability of a virtual collaborative interface for the task of fragment reconstruction. Manipulating fragments a virtual environment can be awkward and inconvenient for the end user (Poupyrev, Weghorst, Billinghurst, & Ichikawa, 1997) because the virtual object does not provide adequate tactile feedback, and the methods of object control are abstract rather than direct.

Current research in heritage and antiquities focusses on 3D scanning and screen-based visualization of artefacts. This research has already demonstrated the potential of 3D scanning technology for 3D cuneiform representation (Woolley et al., 2001). Anderson & Levoy (2002) build on this early research, suggesting the use of 3D visualisation and scanning techniques for the analysis of complete cuneiform tablets rather than fragmented pieces. Anderson and Levoy also provide useful technical information about minimum resolution requirements for the accurate reproduction of cuneiform tablets with legible text, and although their paper deals with reconstructed or complete tablets, the arguments in favour of 3D representation remain valid for incomplete cuneiform fragments. Kumar et al. (2003) and Hahn et al. (2006) made use of 3D scanning and visualisation technology in the digital Hammurabi project, producing high resolution textured scans of tablets, and Levoy's advocacy of 3D scanning and visualisation techniques is continued in the 2006 paper “Fragments of the City: Stanford's Digital Forma Urbis Romae Project” (Koller et al. 2006). This paper describes how fragments of the Forma Urbis Romae (an 18 meter long map of Rome produced circa 206 CE) were laser scanned and reconstructed using inscribed surface topology and fragment edges. The paper also discusses the value of manual tagging of topographic features as a key for future reconstructions.

3.2 Automatic Reconstruction

Freeman and Garder approached the problem of automatic jigsaw reconstruction in the late 1960s, and guided by the limitations of computational power at the time, developed an apictorial solution to the problem (Freeman & Gardner, 1964) which, it has been argued is fundamental to the entire field of object reconstruction (Goldberg et al. 2002). While a much simpler problem(Jacob, 2012), finding the solution of 2D, apictorial jigsaw puzzles is not unlike the more complex 3D issue of cuneiform fragment reconstruction. Checking for an accurate fit in 2D or 3D is a computationally expensive task, as can be seen when examining the work of Papaioannou et al. (2002) and Koller et al. (2006). As a subset of the polyomino packing, mosaic, and jigsaw problem, the process of cuneiform reconstruction can be considered to be NP-Complete (Altman, 1989; Demaine & Demaine, 2007), and so it would be wise to consider heuristic approaches to the reconstruction problem.

The paper “Globally Consistent Reconstruction of Ripped-Up Documents” (Zhu, Zhou, & Hu, 2008) introduces a global method for the reconstruction of 2D paper fragments, which are specifically noted to be a special case of the archaeological fragmented object problem. The different approaches to matching are briefly discussed, and a distinction is made between string based (scale dependent) and feature based (scale independent) matching algorithms. The focus of the approach applied by this paper is the disambiguation of possible matches, based on a global analysis of matched pairs. The paper also notes that general algorithms used for the solution of the jigsaw problem are not ideal for the reconstruction of torn documents. The paper states that jigsaw algorithms generally take advantage of special features only found in jigsaw puzzles, such as regular shape, regular intersection points and easily defined edge pieces.

The limitations of the jigsaw problem are also stated by Kampel and Sablatnig in “3D Puzzling of Archaeological Fragments” (Kampel & Sablatnig, 2004), and the authors introduce the mosaicing problem as a more accurate representation of the problems faced in archaeological reconstruction. Kampel and Sablatnig break down the entire process of 3D puzzling into the categories of acquisition, orientation, classification, and reconstruction. Each of these areas is tackled individually, although the emphasis of the paper is on the orientation and reconstruction of fragmented artefacts. Kampel and Sablatnig also provide some useful advice on the problems faced in archaeological fragment reconstruction. The matching algorithms employed by Kampel and Sablatnig involve pairing the profile curve and size of individual pieces to calculate a candidate match, and since the algorithm is O (n^2), they also advocate the use of heuristic algorithms to solve the matching problem.

It should be possible to mitigate the worst case complexity by a combination of heuristics and preprocessing of the source data. A number of more generalized algorithms could be adapted to select or orient particular fragments for reconstruction (Kleber & Sablatnig, 2009). For example, the popularity of Optical Character Recognition (OCR) software has ensured that a number of language independent methods exist for recognizing the orientation of written data (Hochberg, Kerns, Kelly, & Thomas, 1995; Lu & Tan, 2006), and it is probable that these can be adapted to suit the cuneiform text found on the tablets. Pre-orientation of tablet fragments using this method could reduce the computational load of the fragment matching process significantly. Cuneiform markings themselves could be retrieved using a thresholding filter that can create a 2D map of the rate of change of height across the surface of the tablet. This method of surface feature detection has been used successfully in Stanford's Forma Urbis Romae project.(D Koller & Levoy, 2004; David Koller et al., 2006; Laugerotte et al., 2004). Alternatively, more specific progress has been made in this field by Mara et. all (Mara, Krömker, Jakob, & Breuckmann, 2010), and more recently by Fisseler et. all (Fisseler, Weichert, Uller, & Cammarosano, 2013), who present a novel approach to perform fast 3D script feature extraction from 3D models using parallel computing and GPGPU. There is additional evidence to support the idea that GPU processing using CUDA technology may be an effective tool for reconstruction tasks at the desktop level (Boyer, El Baz, & Elkihel, 2012; Onsjo & Aono, 2009; Schatz & Trapnell, 2007).

Analysis of the fractal dimension (Wong et al., 2005) of an edge might also provide a useful index for sorting potentially matching edges. Further pre-processing of data could be used to generate a list of the angles for all corners of a tablet fragment. These low volume lists of angles could be searched quickly to identify potential matches, or used to generate simple polygon models as shown in (Masayoshi, Shohei, & Hidenori, 2001).

Most recently, (Collins et al., 2014) describe a novel method of automatic reconstruction, developed specifically for use with cuneiform fragment models. This method relies on several techniques to narrow down the list of candidate matches for a fragment pair. Preprocessing of the fragments to unify alignment by using the minimum bounding box and text surfaces is used, followed by a GPU based ranked, pair-wise matching with a cost function which allows for chips and abrasions in the matched surfaces. Even with this specialised algorithm, the authors note that as the number of fragments increases, the likelihood of false positives is still an issue, and the need for human intervention in the system becomes increasingly necessary.

3.3 Crowd Sourcing and Citizen Science

The technologies now available for 3D visualisation, recording, and automated matching present a great opportunity for scholars to delegate the task of reconstruction. By distributing high quality 3D models of cuneiform fragments, scholars are able to remove much of the uncertainty present in 2D scans, photographs, and illustrations. This delivers the potential to harness the power of human computation through crowdsourcing or citizen science (Nurmikko, Dahl, Gibbins, & Earl, 2012) via the internet.

The value of the human element in the reconstruction process is clear (Beaudouin-Lafon, 2008). With appropriate supporting visualizations the eyes and brain of a human are superior to a computer algorithm (Fekete et al., 2012) and for recognition tasks, the combination of human intelligence interacting with machine processing can be superior to either in isolation(Scott, Lesh, & Klau, 2001).

Crowdsourcing and Citizen Science projects like the Galaxy Zoo (Galaxy Zoo & Zooniverse, 2015) which use human volunteers to classify new images of galaxies, and Cellslider (Cellslider & Zooniverse, 2015) which uses a similar framework to identify potentially cancerous cells, provide a platform for the classification of scientific images that computers are currently unable to match. These projects show how crowdsourcing can be used successfully for human computation, with existing tools being able to connect potential participants with researchers for free (CrowdCurio, 2015; Zooniverse, 2015). Other services like Amazon's Mechanical Turk (Amazon, 2015) provide a framework for participants to bid and work on a variety of projects in exchange for money. The success of these projects suggests another potential method for the reconstruction of artefacts, with a virtual environment providing an interface for paid or voluntary human workers.

As humans are the most important part of the crowd-sourced reconstruction scenario, the performance and abilities of these human workers must be considered. It has long been recognised that some individuals have an unusual faculty for reconstructing fragments. Speaking of George Smith’s appointment as a ‘repairer’ at the British Museum in the 1860’s, E. A. Wallace Budge wrote(Budge, 1925) that

“His work was to go over the fragments of inscribed tablets from Nineveh, and to find out those fragments that could be rejoined, and his facility in identifying the nature and character of the inscriptions upon them enabled him to make many remarkable joins."

In the case of Smith, the ability to rejoin the fragments came from his fluent understanding of cuneiform characters, but it is reasonable to assume that an individual’s cognitive style and previous experience with 3D problem solving tasks may affect their ability to reconstruct cuneiform fragments. Indeed, this possibility is reinforced by several studies which tie Field Independence (FI) to increased capabilities in visuospatial tasks like jigsaw puzzle solution(Hong, Hwang, Tam, Lai, & Liu, 2012). Other studies indicate that age and gender may also affect the performance of individuals in reconstruction tasks (Hoyek, Collet, Fargier, & Guillot, 2012; Zacks & Michelon, 2005).

If the ethical considerations of wages estimated in the range of US$ 1.25 per hour for Mechanical Turk (Ross, Irani, Silberman, Zaldivar, & Tomlinson, 2010), the lack of worker's rights (Fort, Adda, & Cohen, 2011), and potential security concerns can be avoided, the potential power of crowdsourcing is difficult to dismiss. More recent papers than Ross *et al.* (Martin, Hanrahan, O’Neill, & Gupta, 2014) indicate that the statistics and demographics of the market have changed since the publication of their paper, and that the current statistics point toward a more ethical, better paid model of working. However, the issues associated with security still exist, and with the collapse of the Safe Harbour agreement in 2015 (European Court of Justice, 2015) it can be argued that the safety of any submitted metadata is now at even greater risk.

3.4 Physical Reconstruction Mechanisms

Manipulation of real world objects is a common and largely unconscious but complex action that can occur bilaterally with minimal physical or cognitive load. At the most fundamental level, a considerable body of literature exists that seeks to produce an effective taxonomy for the basic prehensile actions of grasping with respect to the anatomy of the human hand. (Iberall, 1987; MacKenzie & Iberall, 1994; Wang, MacKenzie, Summers, & Booth, 1998)

In the virtual world, the process of effective object manipulation is less straightforward (Axelsson et al. 2001; Wideström & Axelsson 2000). The basic operations of object selection, rotation, positioning (Bowman et al. 2004), (and most importantly for the process of reconstruction) attachment (Jung et al. 2014) with a keyboard and mouse become an abstract task that require the user to interface with the object indirectly (Kjeldsen & Hartman 2001). The mouse reduces the user to unilateral manipulation of a virtual object by a device designed for 2D navigation with 2 degrees of freedom (DOF), while the process of manipulation and translation requires in 3D requires 6 DOF.

In addition to reduced dexterity, sensory information is stripped away from the user in the virtual world. Relying on conventional hardware means the user will receive no haptic feedback, which has been shown to play an important role in the process of object manipulation (Unger et al. 2001; Lécuyer et al. 2002; Petzold et al. 2004). It is not surprising to discover that experiments have already shown that excluding difficulties created by extremes of mass or scale, the process of object reassembly is generally much slower in the virtual world than the real world (Boud et al. 2000).

Newer gestural interfaces like the LeapMotion™ or Microsoft Kinect™ may also be considered as novel methods for interaction, but at this time they lack sufficient resolution for stable manipulation of fragments. Electromechanical polymer screens (Kim, Israr, & Poupyrev, 2013) and holographic haptic devices (Iwamoto, Tatezono, & Shinoda, 2008) may in the future be able to provide tactile surface feedback to users. The detail of the matching surfaces of an artefact are usually so complex that anything less than a high resolution physical reproduction of the fragments such as those produced, for example, by the Creative Machines laboratory at Cornell University (Knapp, Wolff, & Lipson, 2008) would be of limited value in the haptic sense.

The desire for precision also provides a challenge to the reconstruction process. It has been shown that as the required precision of a task increases, so does the time taken to complete the task (Wartenberg et al. 2004). As a specific form of object manipulation, the rotation of objects represented in 2D and 3D have been shown to have a significant effect on the time taken to complete a task. Shepard & Metzler (1971) have shown that the time required to recognize that a pair of 2D perspective representations of 3D objects are identical is a linearly increasing function of the angular difference in the orientations of the objects. If we extend this thinking to matching surfaces in a reconstruction task, the implication is that users viewing a static representation of objects will require more time to recognise matching surfaces as the angles of representation diverge from equity. It is therefore reasonable to assume that a mechanism that facilitates manipulation of the objects quickly through their various DOF may reduce the time taken to compare matching surfaces.

3.5 Virtual Object Representation for Reconstruction

When it comes to the realistic representation of objects using virtual methods, it is worth noting that limiting the provision of extraneous visual information has been shown to improve performance by focussing attention on only elements relevant to the task at hand (Petzold et al. 2004).

True 3D representations are not possible on conventional visual display units, and this lack of depth information may also hinder the virtual reconstruction process. Without accurate depth perception, it is not possible to effectively judge the scale of irregular objects relative to each other, since the viewer must rely on retinal size, shading, interposition, and convergence alone as normal cues used to estimate size (such as familiarity and convergence) can not be applied in monocular visualisations with irregular objects (Proffitt & Caudek, 2003). While the addition of 3D depth information via a 3D monitor would solve this problem, and has also been shown to increase the sensation of immersion and promoted more direct interaction, care must be exercised as stereoscopic 3D has also been found to increase the sensation of simulator sickness and eye fatigue over time (Bang, Heo, Choi, & Park, 2014; Schild, LaViola Jr., & Masuch, 2012; Yu, Lee, & Kim, 2012). For this reason, domestic 3D printing technology may be an appropriate method for visualising scanned fragments in some situations.

3.6 Summary

This chapter has explored contemporary methods for the capture, visualisation, and reconstruction of cuneiform fragments. Research on this topic spans multiple fields, including the related fields of fresco and potsherd reconstruction. In the following chapters we will build on this existing research through a process of practical experimentation.

CHAPTER 4: ANCILLARY INVESTIGATIONS

Ancillary Investigations into Cuneiform Geometry, 3d Printing and 3d Scanning

In the previous literature review chapters, we explored historical and contemporary aspects of the cuneiform reconstruction process. In this chapter, the results of preliminary research and practical experimentation with technologies that may be useful in the field of cuneiform reconstruction are presented. This includes 3D printing and scanning, which are potentially key technologies in the digital preservation and reconstruction process. This chapter also explores ancillary research and development work that supports later experiments. The photogrammetric analysis of cuneiform fragments is described here, which contributes directly to the understanding of cuneiform tablet geometry, and leads to the creation of proxy tablets which are used in later experiments. The design for a virtual framework for the manipulation of these fragments is recorded here, based in part on the results of the observation of behaviours and strategies identified in chapter 5.

4.1 Analysis of Cuneiform Geometry

Photogrammetric analysis of the CDLI database presented a practical resource for three main reasons:

A sufficiently large body of complete tablets were available for study with appropriate copyright.

The tablets were for the most part scanned into the computer using a flatbed scanner, not a digital camera on a stand, and therefore the calculation of their sized based on pixel information was trivial.

Figure 6: 2D image sample modified from (a now unavailable) internet source image, with the contrast adjusted to enhance the edge detail of the fragment. The image has no scale information associated with it.

EXIF data present in the stored images gave appropriate DPI (dots per inch) information about the images.

The images displayed here illustrate the results of a conversion function designed to represent cuneiform edges pieces as 2D waveforms. The original purpose of this conversion process was to produce scale invariant digital waveforms could be indexed and searched by an edge matching algorithms. While too naive to work for reconstruction, the algorithm proved a useful tool to investigate the geometric properties of whole tablets, and perform a large scale analysis from the CDLI database, which will be discussed later.

Figure 6 shows a sample 2D raster image, depicting a fragment of cuneiform text. The image is devoid of colour, and has no particular scale information associated with it.

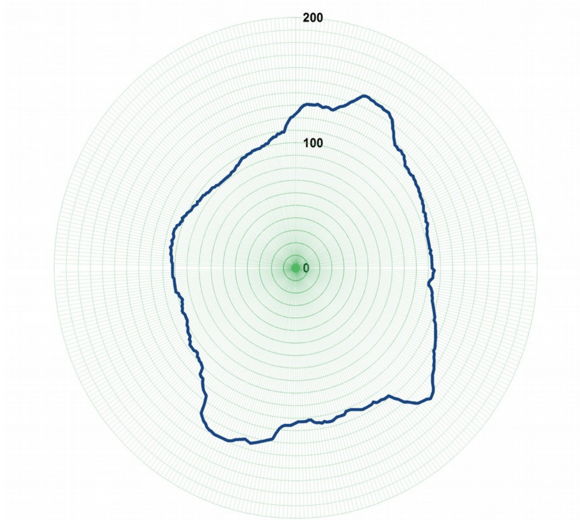


Figure 7: Data generated by the scanning algorithm is represented as a polar graph, showing the close adherence to the original photographic edges.

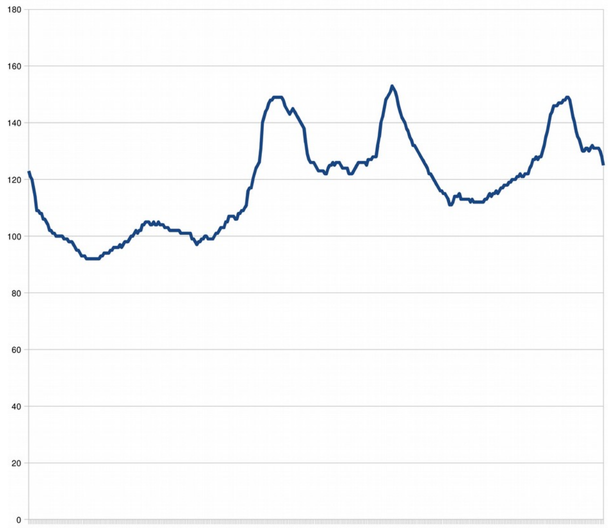


Figure 8: The edge distance detected from center of the fragment, represented in this graph as a Cartesian Figure, with angle of rotation on the x axis, and distance from the center of rotation on the y axis

The algorithm behind the conversion process is very simple:

- Load an image
- Find the centre of the image
- Scan outwards until you find the edge of the object
- Adjust the search path by n degrees
- Repeat from step 3, until the image has revolved completely

The output from the function is a list of values that represent the distance from the centre of the object to the edge. The function accepts an image, the target colour and the number of steps that the image should be rotated. A setting of 360 steps would rotate the image 1 degree at a time, and setting 720 steps would rotate it half a degree at a time. A simplified example of this process is shown in Figure 9.

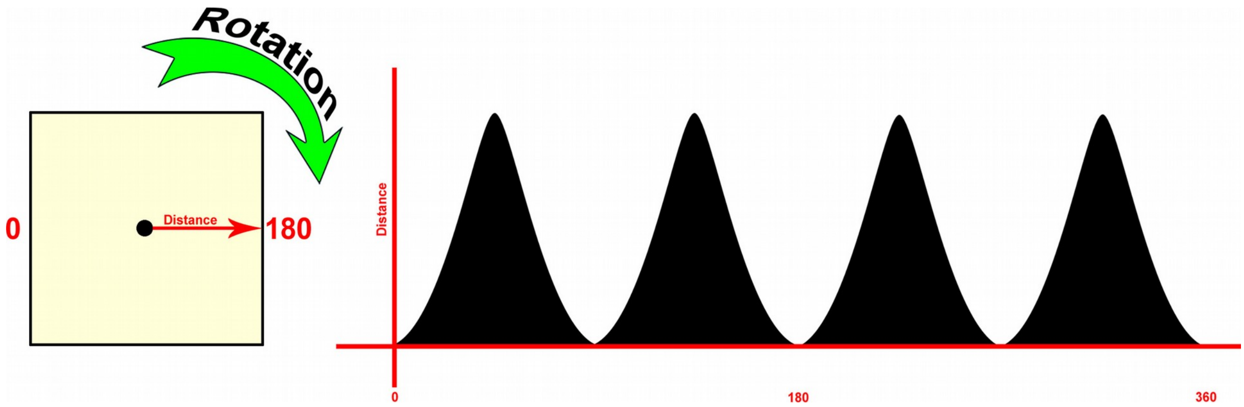


Figure 9: Rotating the image 360 degrees and measuring the distance to the edge at 0.5 degree intervals will result in a Figure containing 720 distances. In this figure it is possible to see the four peaks generated by the four corners of the square as the algorithm progresses from origin to unity.

The result of the conversion process on an actual sample image is shown in Figure 8. The entire image has been converted to a unique wave form that represents the edges of the sample in a complete and accurate way. The integrity of the waveform can be confirmed by a direct comparison of the amplitude at origin and unity, since these points are medial on the polar graph. A visual confirmation of the algorithms accuracy can be made by plotting the waveform as a polar graph, as shown in Figure 7. The shape of the graph in Figure 7 is entirely congruent with the edges of the object in Figure 6 showing that the waveform is an accurate representation of the objects edges.

In the original algorithm, the waveform was further manipulated to remove spurious scale information. This was done by subtracting the minimum amplitude of the waveform from all values (removing any offset in the y axis) and then normalizing the resulting data. For the purposes of photogrammetric analysis, the removal of the offset was not necessary, however this was done facilitate future potential matching of fragments using scale invariate match algorithms. The results of these operation are shown Figure 10 and 11 for completeness.

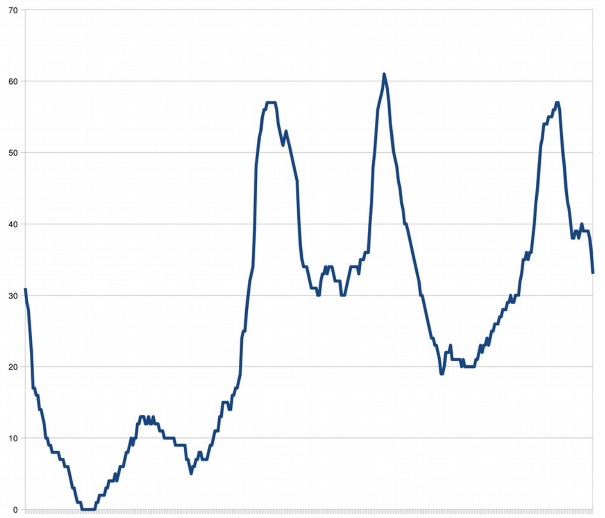


Figure 10: As Figure 8, this graph shows the waveform of the object's edge generated by the scanning algorithm, but in this case the waveform clipped to remove the offset information.

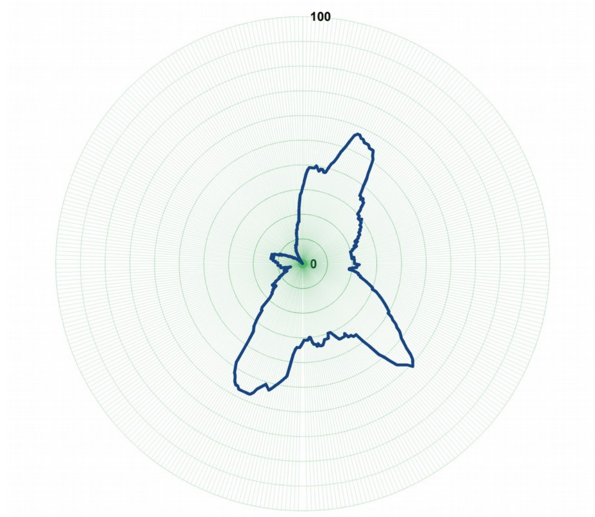


Figure 11: : This polar representation shows the same data as plotted in figure Figure 7, but with waveform clipped to remove spurious scale information (as in figure 10).

4.1.1 Python Code

The python code used to test the theory is was considered disposable, and would have been completely re-written with threading support and more efficient edge detection algorithms if its value extended beyond preliminary testing. it was estimated that the execution time of the algorithm could be reduced by at least 400% using basic optimization techniques. The code in the initial prototype output data directly to the python interpreter, and the information can was then imported into R, SPSS, or a simple spreadsheet. The code is included in Appendix for completeness.

4.1.2 Methodology

The Python script was used to parse the CDLI database, download, and store images that were candidates for analysis. Candidacy was determined by the size and histogram of the downloaded images. Files of less than 20 kilobytes, images with a DPI lower than 150, and achromatic images were all discarded automatically.

Unfortunately, it was not practical given the sample size to differentiate between complete tablets or fragments automatically, so manual sorting of source images was employed to separate fragments and remaining invalid images from valid sample data.

The final set consisting of 8078 samples was passed to another Python script, which scanned each image vertically and horizontally using a simple threshold measure based on the background colour of the image. The largest values from scans in the X and Y axis were used to determine the width and height of the tablet, using the DPI of the scanned image to facilitate the conversion from pixels to millimetres.

The accuracy of the photogrammetric measurement script was tested by direct comparison with known correct data from the CDLI database. In all tested cases, the data was found to be accurate within approximately one millimetre of the recorded values. The resulting data was sorted by period, and analysed using simple statistical methods.

4.1.3 Results

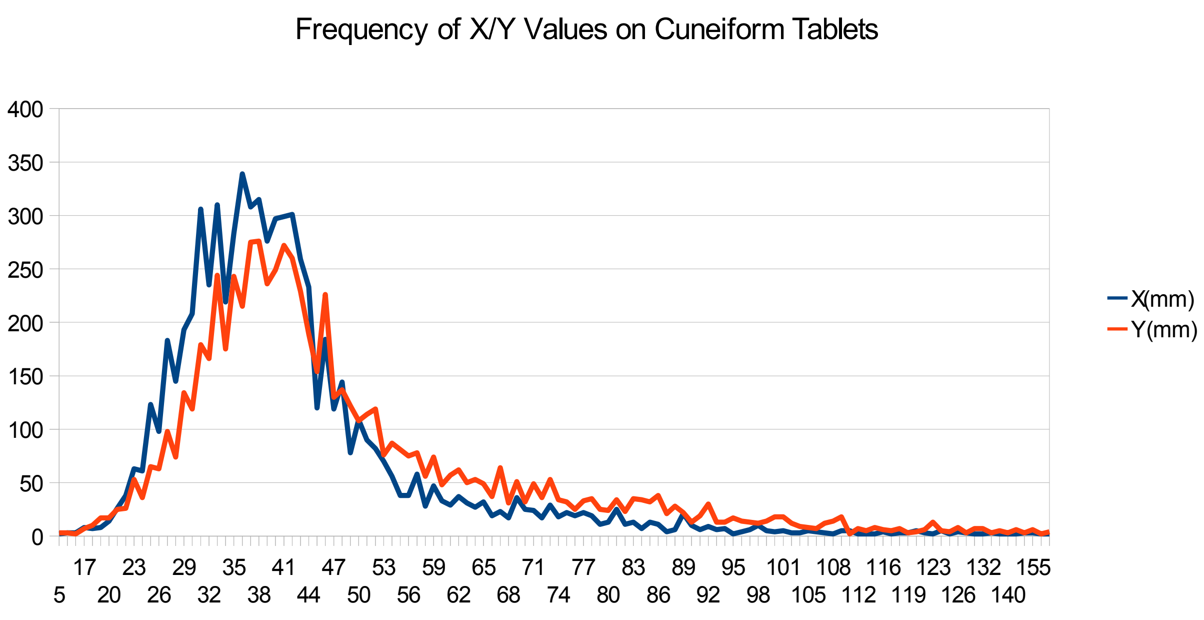


Figure 12: This graph shows the number of fragments of different sizes (in millimeters) for the X and Y axis of complete cuneiform tablets. The peak between 23mm and 62mm is clearly evident.

After processing, the CDLI photogrammetry data reveals that the average size of a cuneiform tablet is 43mm wide by 51mm high. The likelihood that any given tablet from the sample set has a diameter between 23mm and 62mm is over 88%, and a similar range between 25mm and 76mm for the height of a tablet yields a probability of roughly 85%. Figure 12 shows the distribution of width and height for the X and Y axis. An analysis of ratio between width and height for each tablet has shown that the shape of tablets is far from random. The sample shows a marked bias towards an approximate width to height ratio of 1:1 and a lesser bias towards a golden ratio conjugate of 0.625:1. Figure 13 illustrates this relationship between width and height.

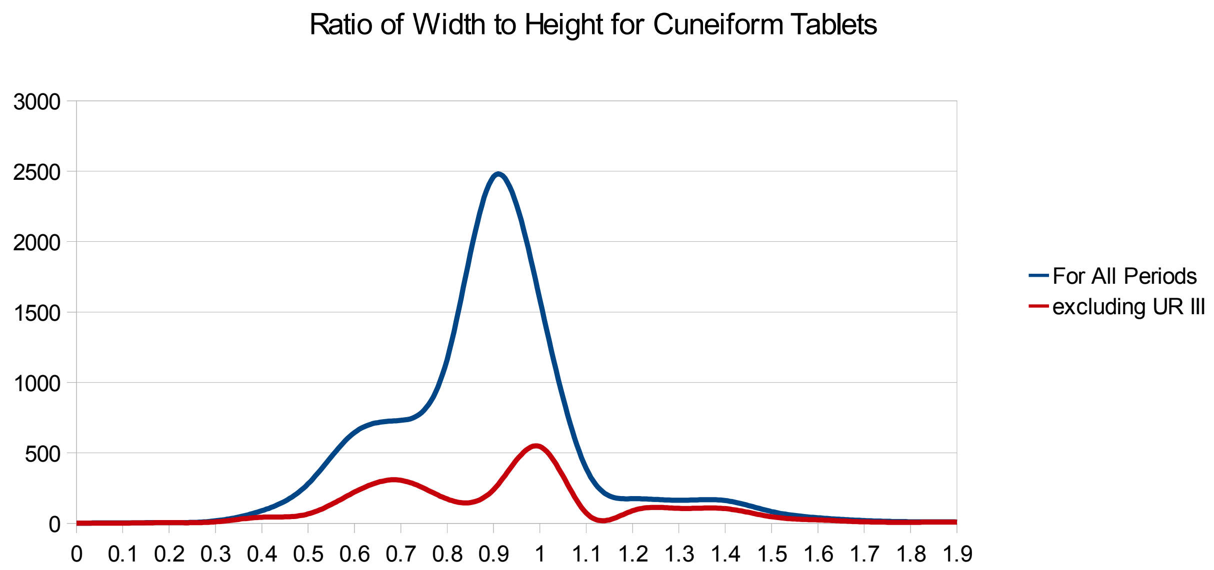


Figure 13: Figure showing the ratio between the width and height of cuneiform tablets. The peak at ratios of 1:1 and 0.6:1 can be seen across all periods.

It is important to note that a large proportion (approximately ¾) of the analysed tablets are from the period UR-III. In order to ascertain whether the ratio bias was a phenomenon associated primarily with the period UR-III, a separate analysis was made that excluded results from this period. As Figure 13 shows, the 1:1 and 0.6:1 trend still seems to be present in the filtered subset of data.

Figure 14 provides a deeper analysis of the ratios by era, showing that the range of ratios does seem to cluster around the averages of 0.6:1 and 1:1 depending on the period.

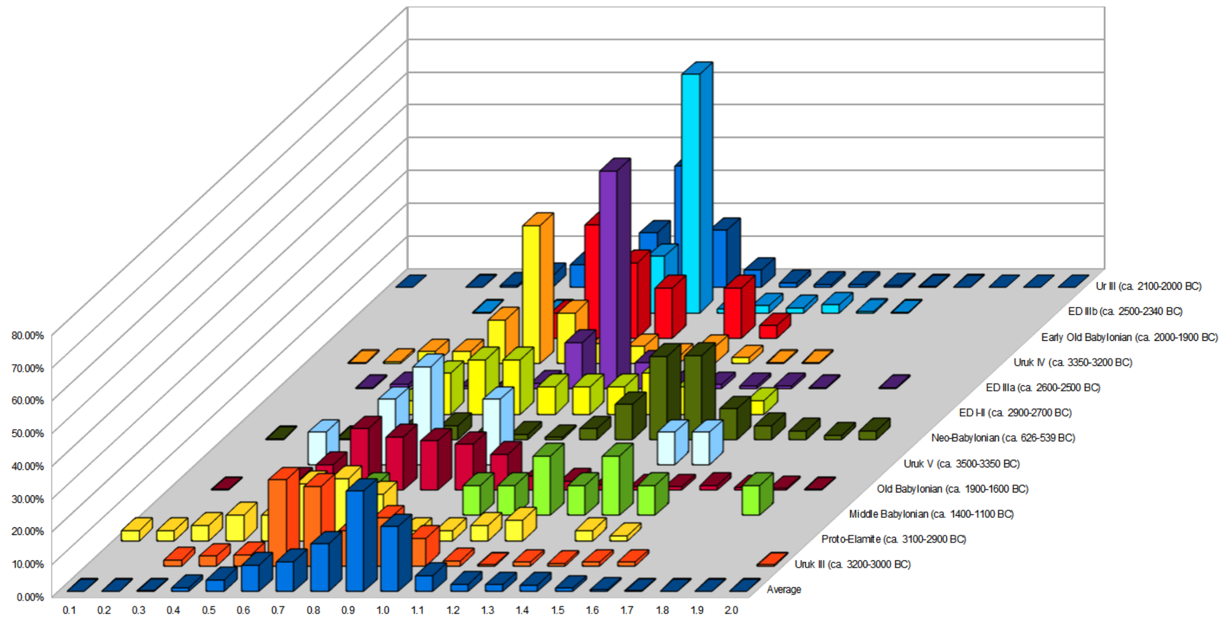


Figure 14: The ratio of tablet width to height is shown here, broken down by historical period. With the exception of Neo Babylonian and Middle Babylonian, the bias towards the ratio of 1:1 and 0.6:1 is relatively clear.

4.2 3D Printing for Cuneiform Reconstruction

One of the principal feedback systems involved in manual cuneiform reconstruction is the tactility of a physical fit. The haptic feedback encountered when reassembling fragments of stone or clay can provide a strong indication of whether two fragments fit together. In addition to this, manual reconstruction allows for the direct manipulation of fragments in a 3D space. In virtual reconstruction systems, the user is abstracted from the direct interactions of the physical world by a keyboard or touch screen, and manipulation of fragments by remote control is clumsy in comparison to direct manual reconstruction.

Modern domestic 3D printing technology makes it possible to reproduce cuneiform tablets using plastic or resin, and give the feedback of manual confirmation to digitally matched fragments. An additional benefit of this technology is the ability to place physical copies of fragments with scholars who may previously have had access to photographic resources. Also, fragments may be rescaled before printing to allow for more accessible study or demonstration of a particular text. In short, 3D printing technology has the potential to provide each and every student of cuneiform studies and member of the general public with complete, real world access to the entire body of cuneiform source material. 3D printed parts are not precious or fragile, and so the process of sorting and matching fragments could be carried out by untrained hands. Even museum visitors could be encouraged to try their hand at matching fragments together.

The recent popularization of FDM (Fused Deposition Modelling) printers by the Maker community has made the reproduction of cuneiform tablets an inexpensive possibility. Prior to this, the only avenues for 3D reconstruction relied on the use of expensive powder based or stereo-lithographic resin based printers. This technological leap bears striking parallels to the change from chemical to digital photographic reconstruction in archaeology, and it is exciting to think that we may be at the liminal intersection between technological eras.

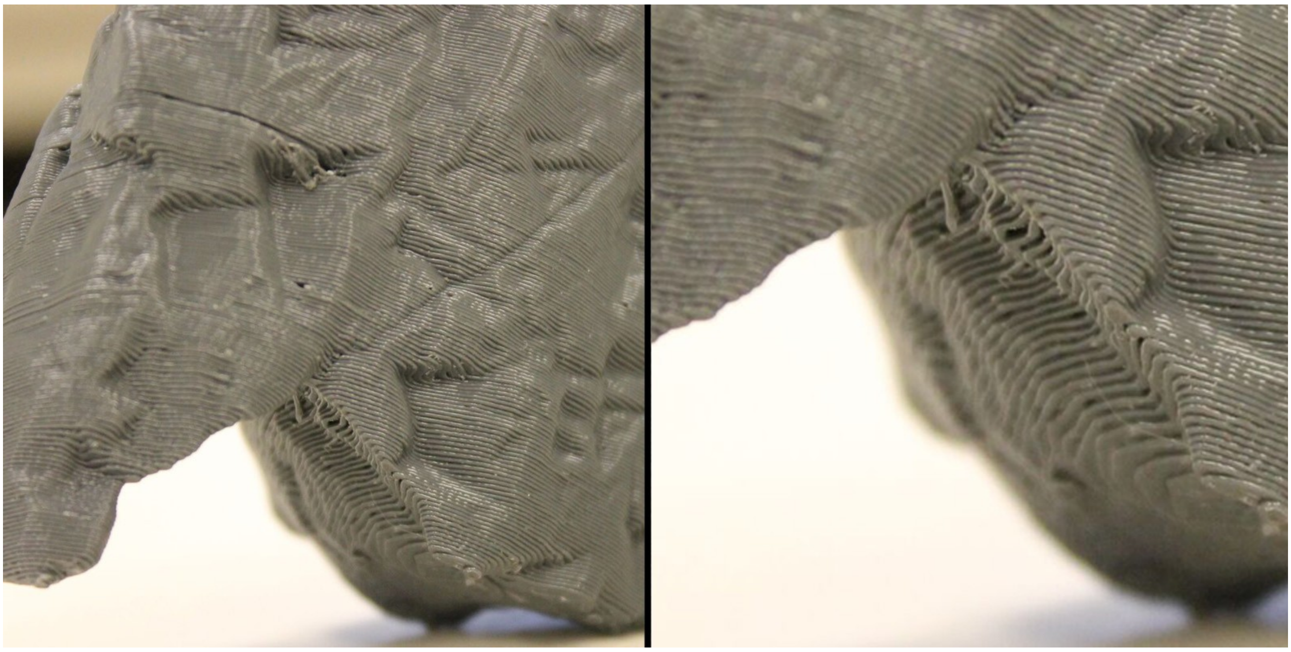


Figure 15: Example of output from an ordinary domestic FDM printer. Striations in the z-axis are clearly visible, even in this large (approx. 50mm) model. The orientation of these striations may affect the legibility of the text on a printed fragment, prevent the accurate reconstruction of printed fragments, or potentially misdirect individuals attempting to reconstruct the fragments.

Despite the lower resolution of these systems (see Figure 15), this project project and other projects like the Cornell Creative Machines Lab (Ju, 2011; Knapp et al., 2008) have shown that the reproduction of 3D cuneiform fragments using low cost off-the-shelf 3D printers is possible in a variety of materials, principally PLA (Poly Lactic Acid) and ABS (Acro Butyl Styrene) plastic, with an accuracy of less than 100µm in the Z axis. However, (D V Hahn et al., 2006) note that well preserved cuneiform tablets can have markings with distinct features of 50µm, and this places a very tight restriction on the quality of FDM prints that scholars may feel are acceptable. Additionally, the limitations of human touch have recently been shown to extend to the range of 10µm (Skedung et al., 2013), a range outside the ability of an off-the-shelf FDM printer.

There are two methods for dealing with this problem. Firstly, the fragments being reproduced can be enlarged to increase the visibility of the details. This is a simple process, but requires that the scaling factor must be uniform across of the printed fragments, or matching would be impossible. Also, the visibility and tactility of printed layer will still be visible, and the stratification of the deposited layers may give a false impression of a fragments correct orientation, or prevent a close fit between two cogent surfaces. The alternative method is to produce a more accurate printer capable of working at resolutions of <50μm. While this is a difficult task to accomplish, it means that tablet fragments could be reproduced at their original size with full detail. The accuracy of a 3D printer depends on a number of factors, including the rigidity of the frame, the smoothness of the bearings that support the print platform, and the size of the extrusion nozzle. In order to create a printer with a high resolution, it was decided that a stainless steel frame construction based on the Reprap design would be preferable (see Figure 16).

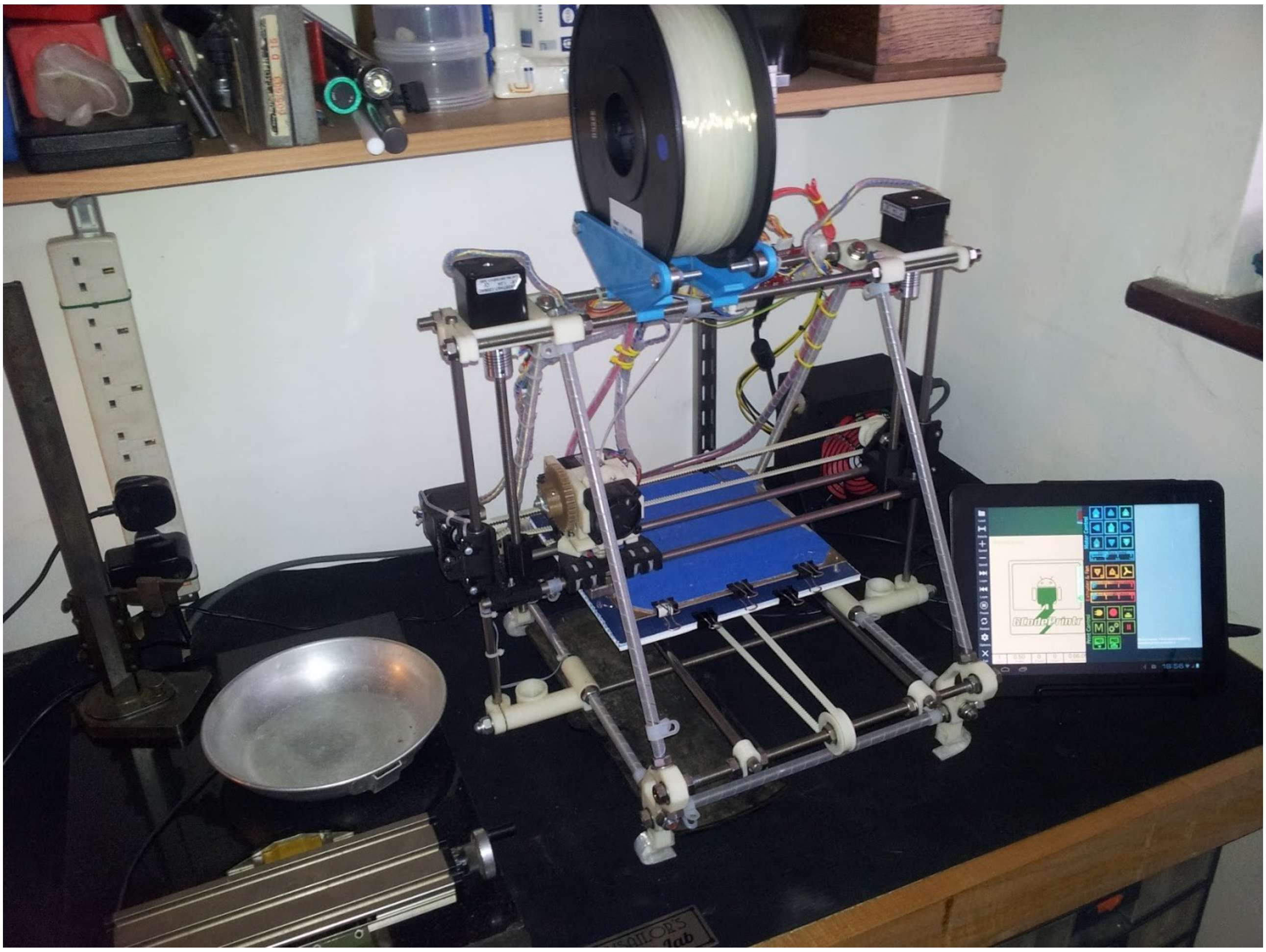


Figure 16: The completed high resolution Reprap printer, operating under control of an Android tablet. The fine nozzle, belt tensioners, and linear bearings all improve the accuracy of the printer. However, the absence of an enclosed build area makes it difficult to print large ABS plastic parts without warping.

The design is easy to assemble and adjust, requires no special welding or mechanical joints, and the entire frame can be cross-braced for additional support where necessary. Linear bearings and runners were used instead of bushings, and belt tensioners were used to minimise the effects of stretching. Additionally, an aluminium decoupler was used to reduce the effect of any minor misalignments in the z-axis drive assembly. This decoupler effectively allows the worm-toothed drive-gears to move and flex at the joint between the shaft and the motor coupling, preventing the head from shifting in the X-Y axis if the motor is not perfectly aligned.

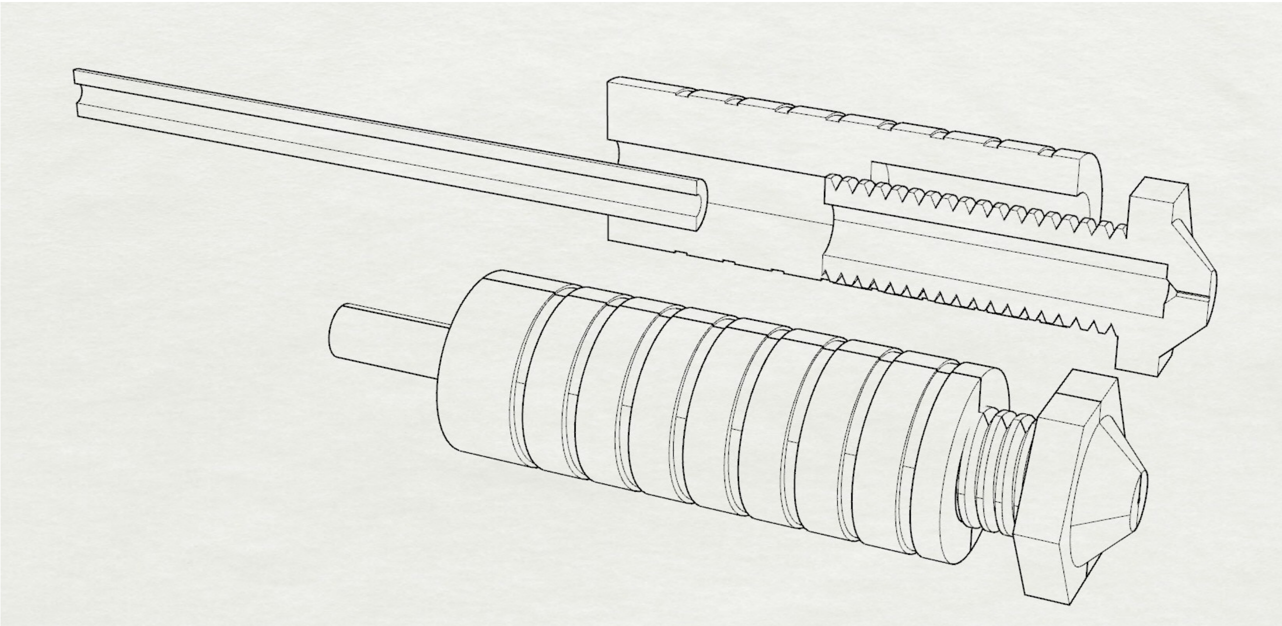


Figure 17: Figure showing the cutaway (top) and assembled (bottom) sketch of the modified 3D printer nozzle design with outer PEEK sleeve, and inner PTFE filament tube. The inner PTFE sheath reduces friction, while the outer rigid PEEK sleeve decouples the hot end of the nozzle from the cool end of the extruder, preventing plastic from heating too early and reducing the force applied by the extruder motor.

The most important modification to the system (assuming that a sturdy chassis is in place)is a custom nozzle assembly with a high powered direct drive that allows the printer to extrude a much finer filament than most 3D printers (Figure 17). A 'standard' off-the-shelf 3D printer typically has a nozzle diameter between 400µm and 600µm, whilst the custom nozzle for this project was 200µm. The benefits of the smaller nozzle are clear, as the finer aperture allows for finer detail to be extruded. The nozzle itself was machined from an M8 brass bolt using a lathe, with a 4mm bore lined with 2mm internal diameter PTFE tube to reduce filament drag. The outlet hole was 2mm deep from the end of the nozzle, and drilled by hand using a jeweller's drill approximately twice the thickness of a human hair.

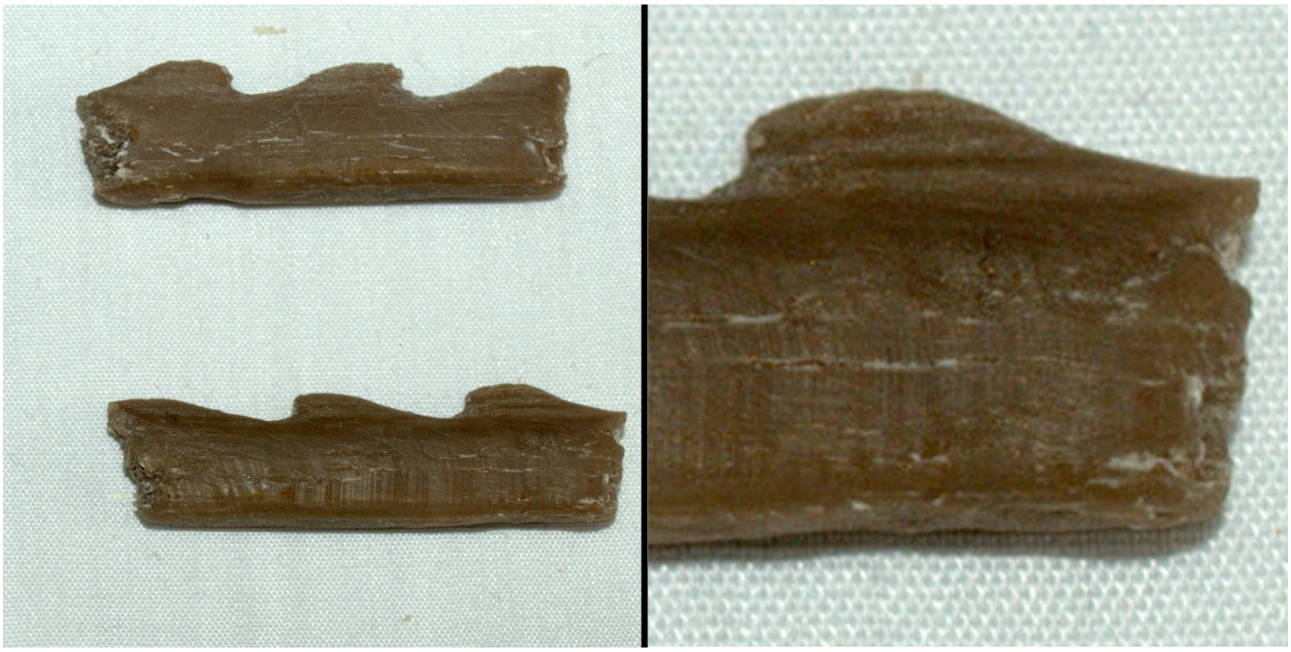


Figure 18: Print of another antler fragment from Star Carr, produced using the modified printer with 200μm nozzle. z-axis resolution for this print was 10μm. The material was ABS plastic. The quality of this print out is much higher than a domestic 3D printer, but it is also much slower.

Reducing the nozzle diameter 400μm to 200μm increases the pressure on the filament by a factor of four, so the possibility of filament slipping against the drive gear was a problem. To solve this, an actively cooled direct drive extruder was used with an extended nozzle attachment constructed from machined PEEK (Polyether ether ketone) rod. The heat-resistant peek rod was used to increase the separation between the hot and cold end of the extrusion head, and to increase the effective cooling surface of the head. This additional cooling improved the rigidity of the filament at the cold end, allowing the drive gear to grip and feed the plastic filament more effectively. When combined with a heavy duty spring to apply additional pressure on the filament guide, no slippage occurred while using ABS plastic. However, PLA plastic was less effective when extruding though the 200μm aperture, with slippage and jams occurring on occasion due to the inherently high friction co-efficient of the material (Jimenez, 2014). While this could be tempered to some extent by increasing the temperature of the head, there was a point beyond which the PLA plastic would begin to degrade from the thermal stress.

Figure 19: Print of an antler fragment from Star Carr, produced using the modified printer created for this project using a custom made 200µm nozzle . The z-axis resolution of this print was 10µm. The material was ABS plastic.

The effect of the smaller nozzle diameter is a reduced extrusion volume, which means that much finer detail can be reproduced (see Figures 19 & 20). However, as the number of vertical print layers increases, so does the time required to print an object, with even small objects taking in excess of two hours to print. In the absence of an enclosed and heated build area, this increased build time also means there is a risk that internal cooling processes within the printed fragment could cause the object to shrink out of shape or even fail completely. For PLA plastic this effect is negligible, but for ABS, the final print may shrink by as much as 3% when cooled. This means that objects larger than a few cm are more difficult to print, and may take several hours to complete.

Additional care must be taken when attempting to match fragments together printed using different types of plastic, and the colour and type of plastic used can have a marked effect on the level of material shrinkage encountered as the fragment cools.

4.3 3D Scanning for Cuneiform

This project has utilized multiple scanning technologies that rely on both laser and structured light. The David Scanner software (by David 3D Solutions) is one such solution, and a scanner built with this software it's foundation, and a customized portable scanning platform built using commercially available parts (Figure 20).

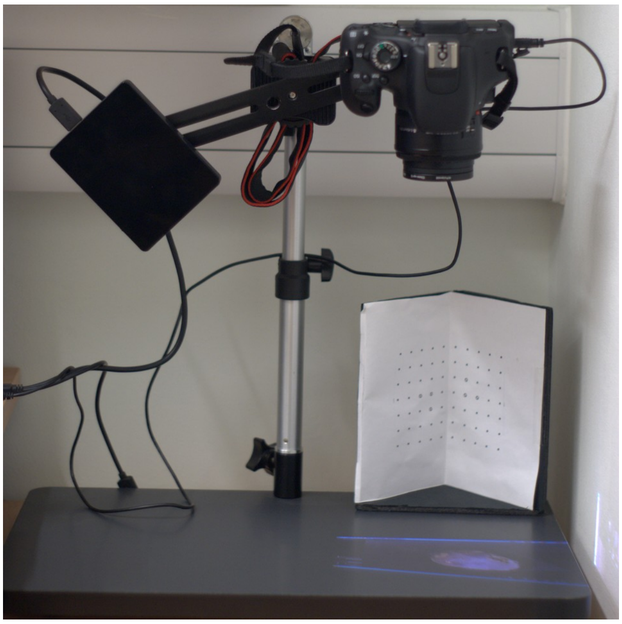


Figure 20: Image showing the David 3D scanner setup with projector and DSLR macro lens. The calibration corner is visible in the right of the image, below the camera.

The scanning platform is built around a telescopic photographic copy stand, with a wide aluminium flash bar holding an Acer C10 projector and Canon EOS 600D camera. The camera and projector are connected to a laptop computer using a USB connection. Although designed for structured light scanning, this system can also be used with a laser wand to generate a conventional laser scan of objects. A ball-jointed camera mount has been added to the top of the copy stand to allow for free mounting of the scanning head. The free range of motion of the head makes it easy to scan in vertical or horizontal configurations.

Unlike many other structured light scanners, the scanner described here uses a very low intensity projection system. This lower intensity beam allows the scanner to project structured patterns that can still be detected in normal light with an ordinary camera, but are sufficiently weak to prevent excessive subsurface scattering and reflection. Linear polarizing lenses can also be used to minimize scattering of the projected contrast point.

The accuracy of a structured light system depends on a number of factors, including the hardware used and the size of the object being scanned. The resolution of the camera and the projector are most important, since the resolution of these will determine the maximum number of points that the scanner can sample in one scanning pass. If the maximum size of a scanned object is 1000mm square, then the maximum resolution of the scan using an 800x600 webcam and projector will in theory be (800*600)/1000, or 480 samples per mm. In practice however, this resolution would be lower, as it is unlikely that the projector and camera could be calibrated perfectly together.

While a commercial laser scanner typically uses finely ground optics and high quality visual sensors, domestic cameras and data projectors have lower precision optics. The effect of these cheaper optical components is most noticeable on low-end webcams, where aberrations will occur around the edges of a captured image. These visual distortions affect the ability of a structured light scanners to make accurate measurements, and so they must be corrected before any scanning takes place. In general, better quality equipment will yield a more accurate result, although some corrective methods can be used to map the inconsistencies of a lens. The David scanner employs a multi-step calibration procedure with a standardized calibration corner to detect lens characteristics and aberrations, and to pair the projector output with the configuration of the scanning system. This calibration process needs to be performed whenever the focus or orientation of the scanner/projector is changed, but recalibration is not necessary for global changes in orientation. Because the calibration process maps imperfections in the lens, it means suitable quality scans can be made using a domestic quality camera. However, it should be noted that structured light scanning employs phased levels of brightness to recover accurate object geometry, so a camera that can differentiate shades of gray with some accuracy is essential. The shutter of the camera being used needs to be sufficiently robust to deal with the full range of illumination presented by the projector. A camera with inadequate (or poorly calibrated) shutter sensitivity will result in a model with a distorted surface.

Figure 21: Scan of a cuneiform tablet replica taken using the David Scanner with macro optics.

Figure 22: A scan from the David Scanner, showing a human fingerprint to illustrate the level of information that can be retrieved.

An advantage of the structured light process is that the projection and shutter settings can be manipulated to allow the scanning of difficult materials. Even metallic objects and black fabric can be captured simultaneously by a structured light scanner using appropriate settings. The reduced light levels also mean that distortions caused by subsurface scattering in opalescent materials can be reduced to a minimum. The scanning process is fast (usually under 30 seconds per scan), and multiple scans of a surface can be taken in under one minute. A complete cuneiform fragment can be fused from 8 scans in approximately 10 minutes, and then exported in a format that an online visualisation system can process. Examples of scans taken using the David scan are shown in figures 21 & 22.

The principal disadvantage of the structured light scanning process is the sensitivity to incidental light. The intensity of structured light projections is much lower than laser line projectors, and environmental lights will reduce the ability of the scanner to capture clean data. For this reason, it is advisable to scan in a light controlled environment, away from direct sunlight. A secondary limitation of the system is the depth of field of the camera when shooting at macro levels. The focal range is reduced to approximately 10mm when scanning at 4x magnification, which is acceptable for cuneiform or fresco fragments, but may cause issues with small statuary and other objects.

4.4 Tablet Proxies

Given the fragility and value of cuneiform fragments, it was decided that virtual fragments would be used in early experiments that involved interaction. A collection of tablet proxies were created using clay, and textured to present an approximation of existing tablets.

Figure 23: Kaolinite tablet proxies before firing. The proxies were created in a material similar to actual cuneiform tablets, and sized appropriately using data collected from existing tablets. The markings were made with a similar density and shape to actual cuneiform text.

Figure 24: Tablet proxies after pit firing. The surface colouring of the fragments is much closer to actual tablets, and the deliberate air inclusions in some fragments have caused those tablets to fracture.

The clay chosen for the proxies was a fine, white, modelling clay with a consistency similar to Kaolinite, as this was similar to the fabric of actual cuneiform tablets(Levey, 1959). To ensure a variety of fracture types, air inclusions were deliberately added to several tablets so that they would fracture during firing.The tablets were air dried (see Figure 23), before being dried on a grid over fire. They were then pit fired using charcoal for 2 hours. Those tablets which did not explode where broken manually using the application of a sheering force.

The character marking on the clay were created by projecting actual cuneform characters onto the surface of the clay tablet at an appropriate scale, and then roughly impressing the character patterns and symbols into the clay using a wedge shaped tool. The characters and symbols were chosen at random from a variety of historical periods, and then used as a guide to create markings. It was felt that having accurately reproduced tablets could bias some tests between experts and non-expert participants, so random characters were used to prevent this.

Although the tablets were not completely fired, they were sufficiently resilient to damage for experiments purposes, with a surface effect that adequately approximated the colour variations found in real tablets. These effects can be seen in Figure 24.

4.5 The Experimental Framework

Figure 25: This image shows the interface of the reconstruction system as displayed on a touchscreen monitor. Note the list of potential matches on the left, the notes provided by users on the right, and the user's collection of fragments at the bottom of the screen.

A distributed human/agent framework for collaborative interactive 3D visualization and matching of cuneiform fragments was created to facilitate further experimentation (see Figure 25). The framework comprises a browser-based interface for the manipulation of multiple fragments, a server based framework to support multiple agents, a database of fragments, and a node.js server that allows real-time communication between different aspects of the reconstruction system.

The browser-based front end is primarily based in JavaScript, and interacts with the MYSQL server database and with a node.js server. The system has been designed so that multiple users and agents can interact collaboratively regardless of their real-world location. Fragment geometry is retrieved by users (and virtual agents) within the system by sending a request to the server. While it is possible to lock fragments for a given period of time so that some actions can prevent an agent from interacting with a fragment for a number of seconds, this limitation does not affect human users of the system, who can interact with fragments freely.

The design of the front-end and the features that it contains is based on user feedback from initial testing using a simple Vizard based interface (as described in chapter 5.1.2), and on the results of a participatory design session (as explained in Appendix C). The actual interface is shown in Figure 26, whilst the results of the participatory session used to create it are shown in Figure 27.

Figure 26: This image shows the interface of the reconstruction system as displayed in a web browser. The left-most panel shows suggested matches for the currently selected fragment, while the right side shows any notes that have been added about this fragment. Addition fragments may be loaded by clicking on the image selection bar at the bottom of the screen.

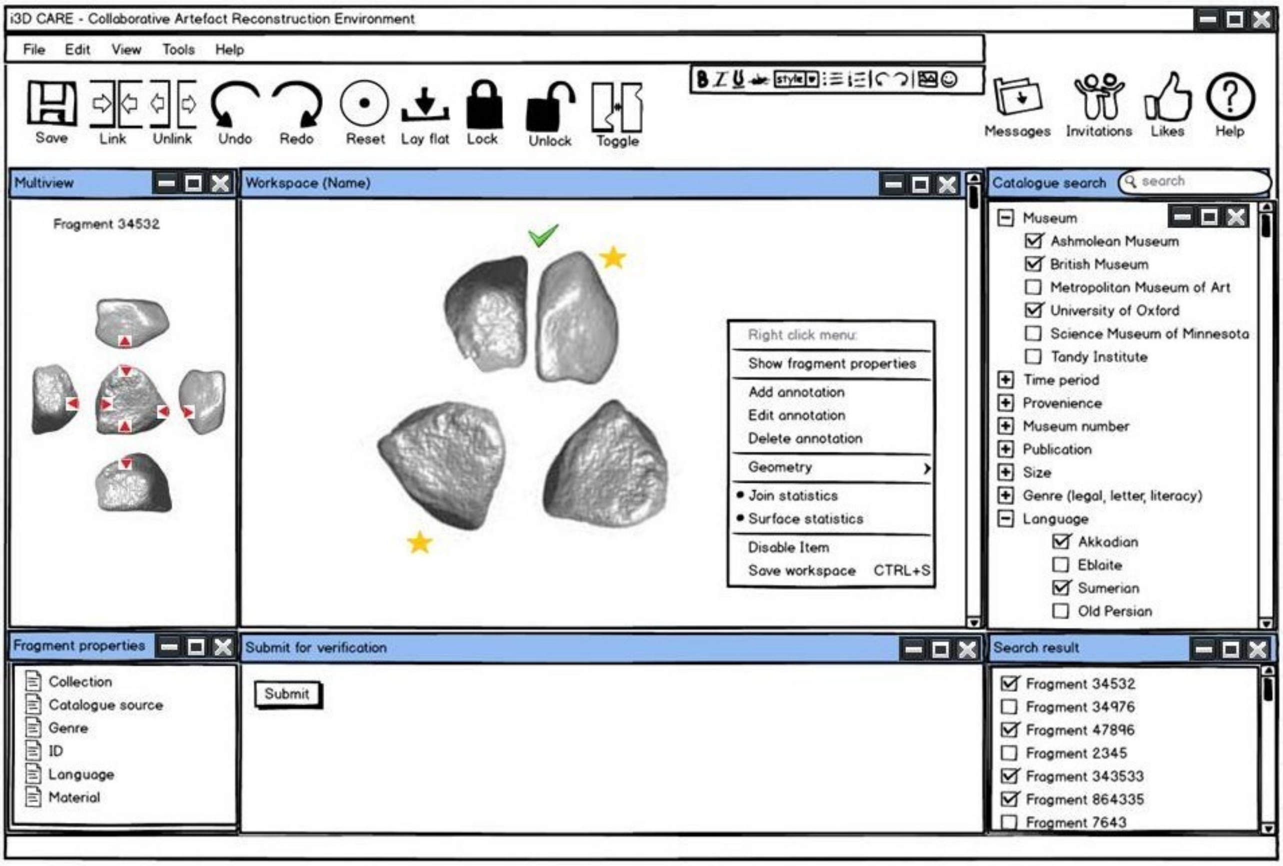


Figure 27: An system interface example created by the participatory design session (as described in Appendix C), incorporating communications functionality and selection for multiple windows. Notice the toolbar buttons for linking, locking, undo, redo and lay-flat features.

4.5.1 Tools & Interface

The user interface contains a number of tools that have been designed specifically to facilitate the virtual reconstruction process. These tools are the product of contextual enquiry and research in related fields.

Redo and Undo

The ability to revert changes made to the position and orientation of fragments was a common request made by users. By using the undo and redo functions, a user can move backwards and forwards through the history of their actions. This functionality protects the user from the effects of their errors, offering an advantage over real world reconstruction tasks.

Fine Rotation

The gimbal manipulator is in essence a virtual dial that the user can manipulate to affect the values that control the position of the fragment on screen. It has been shown that the dial is a good system for this type of selection and has a fast initiation time, but suffers from a high error rate when selecting precise values (Oladimeji, Thimbleby, & Cox, 2013). To counter this, it was decided to implement a keyboard based system for fine control with an up/down style interface that worked alongside the gimbal manipulators. This type of up/down interface has a much lower error rate, and was designed to use the QA, WS, and ED key pairs to allow fine control over the yaw, pitch, and roll of a fragment.

Mouse Selection Rotation

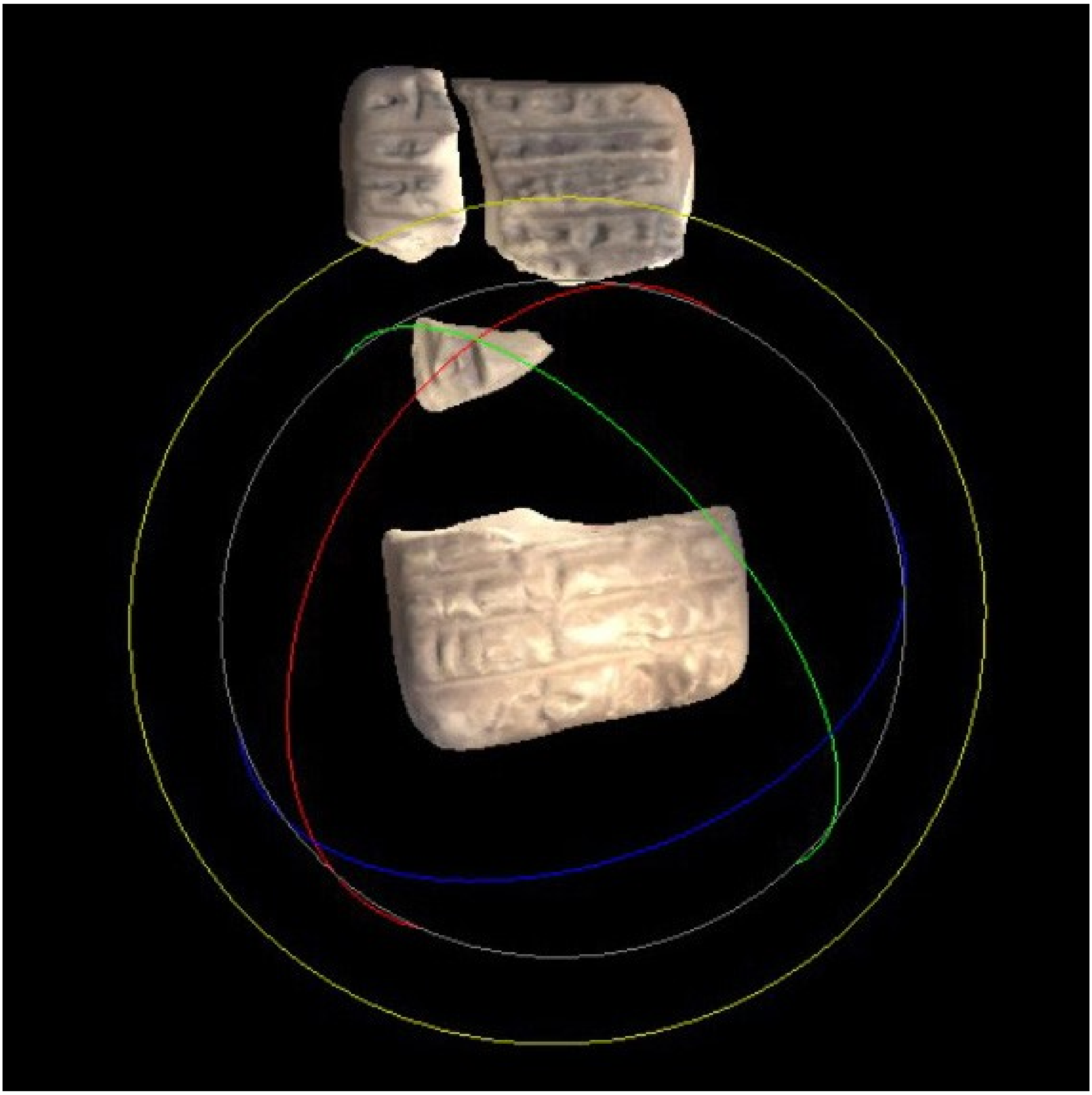


Figure 28: Screenshot showing the gimble manipulator, centered on the bottom fragment. Each axis is represented by a different color, and the outer ring allows for rotation around the axis of the viewing direction.

The mouse allows for direct manipulation of fragments in the virtual environment, facilitating rotation and translation in space relative to the camera. While direct manipulation is intuitive, the small size of the fragments presents an issue for fine control, with experiments showing that the performance of users dips far lower than that which would be expected by Fitt's law, which predicts that the time required to rapidly move to a target area is a function of the ratio between the distance and width of the target object (Bérard et al. 2011). This is supported by (Aceituno, Casiez, & Roussel, 2013) who conclude that the pixel-per-inch (PPI) range of useful mouse resolutions overlaps the PPI resolutions of modern monitor. For the selection of individual pixels on a screen this does not present a problem for precise movement. However, when the task extends beyond pixel selection and into the action of rotation, the granularity of the pixels and the small size of a target object becomes problematic. The small range of movement available restricts the freedom of rotation, and when rotating fragments in multiple dimensions, and the basic computer mouse lacks the degrees of freedom necessary to match the users' conceptual model of the task at hand. To solve these problems, a gimbal manipulator was implemented to handle yaw, pitch, and roll of individual fragments.

With the gimbal manipulator active, the gimbal handles provide a much larger target with clearly defined boundaries for the user to select the axis of rotation. With the gimbal deactivated, the mouse can still be used to drag the fragment to a new location in the virtual space. The activation state of the gimbal manipulator is toggled by a single click of the mouse on the object.

Bring to Front

A recurring complaint in early trials was that the fragments were difficult to see because they were small, and if participants zoomed in the camera to view the fragments then other fragments would be off screen. The Bring to Front tool was implemented so that participants could quickly move a fragment close to the screen to view or manipulate it, and then return it to its original screen position at the click of a button.

Ghost Mode

Unlike jigsaw puzzle pieces or fragments of a torn document, cuneiform fragments are 3D objects, and occlusion of overhanging edges makes it difficult to match fragments together by their overall edge shape. The ghost mode was developed so that a fragment could be made semi-transparent, allowing participants to see clearly how a fragment intersected another fragment.

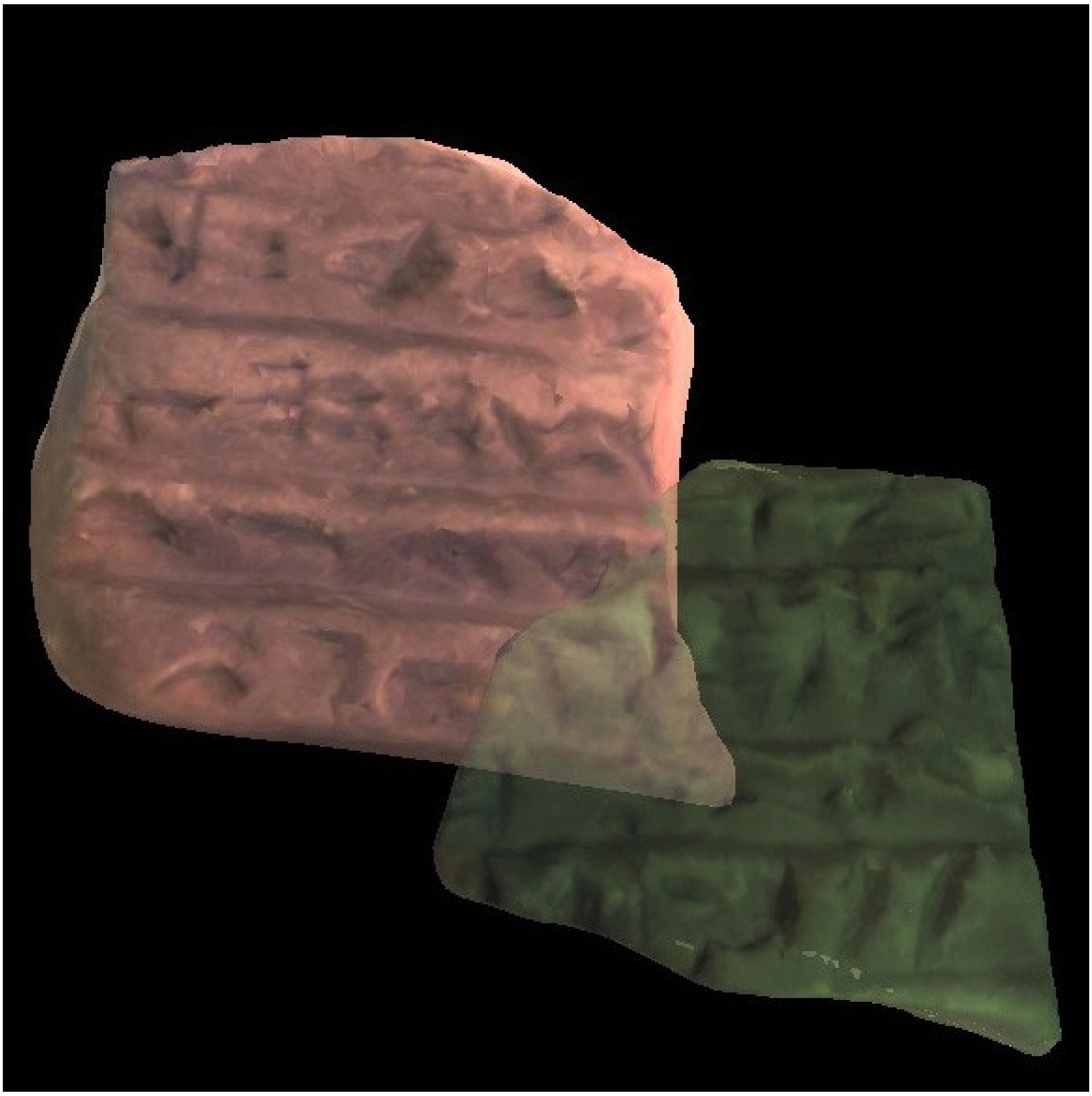


Figure 29: The green fragment in this screenshot is in ghost mode, and is semi-transparent. The user can clearly see from this that the left hand fragment intersects the edge of the green fragment on the right.

Grouping & Gluing

The desire to group objects together and to 'glue' them together so that they move as a single object was expressed by participants during post-testing interviews. This tool makes it possible to group the fragments on screen into distinct groups, and to make those groups move as single objects.

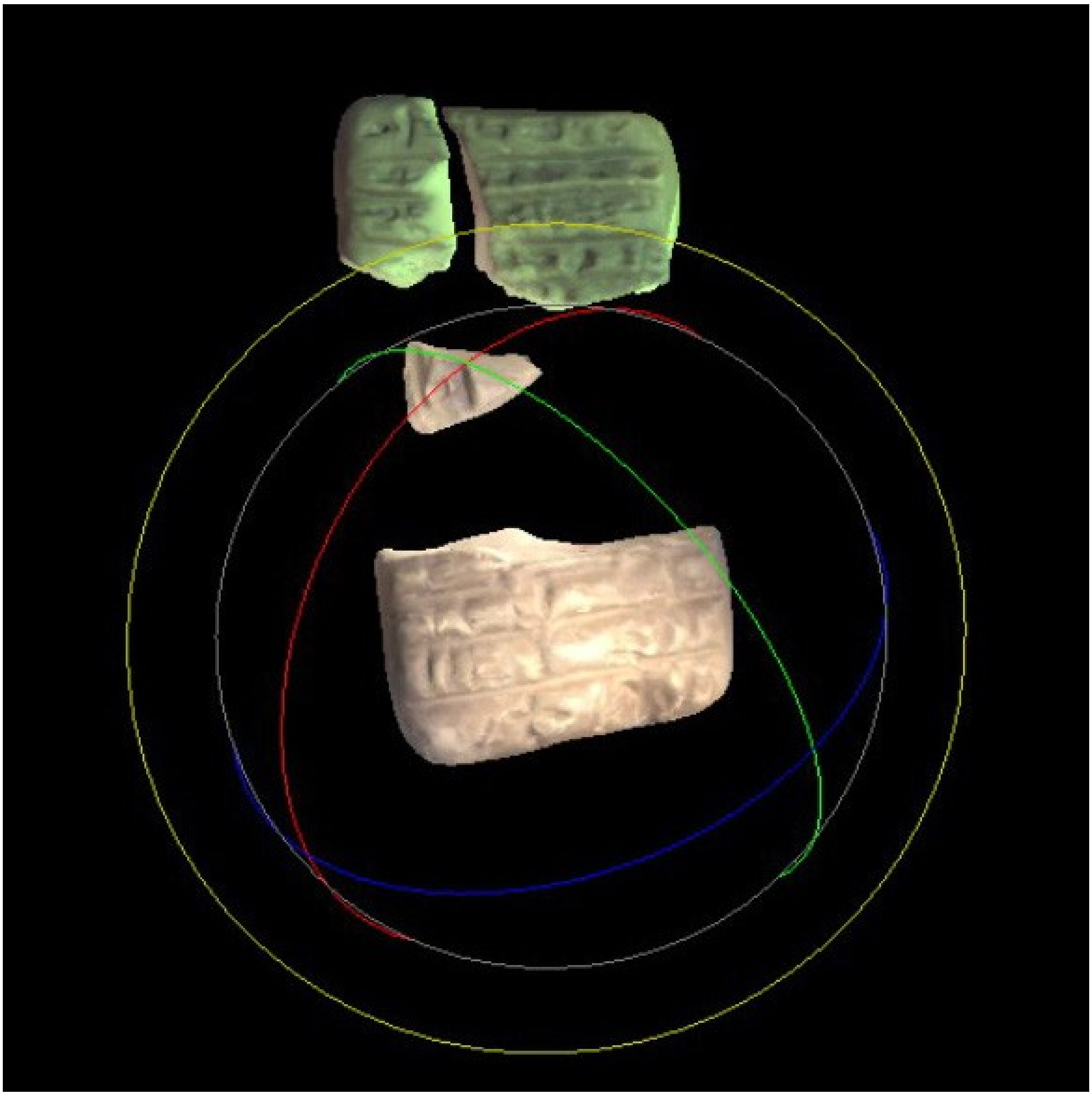


Figure 30: This figure shows how grouped fragments can be identified by their colours, with each fragment in a group having the same colour.

Masked Edges

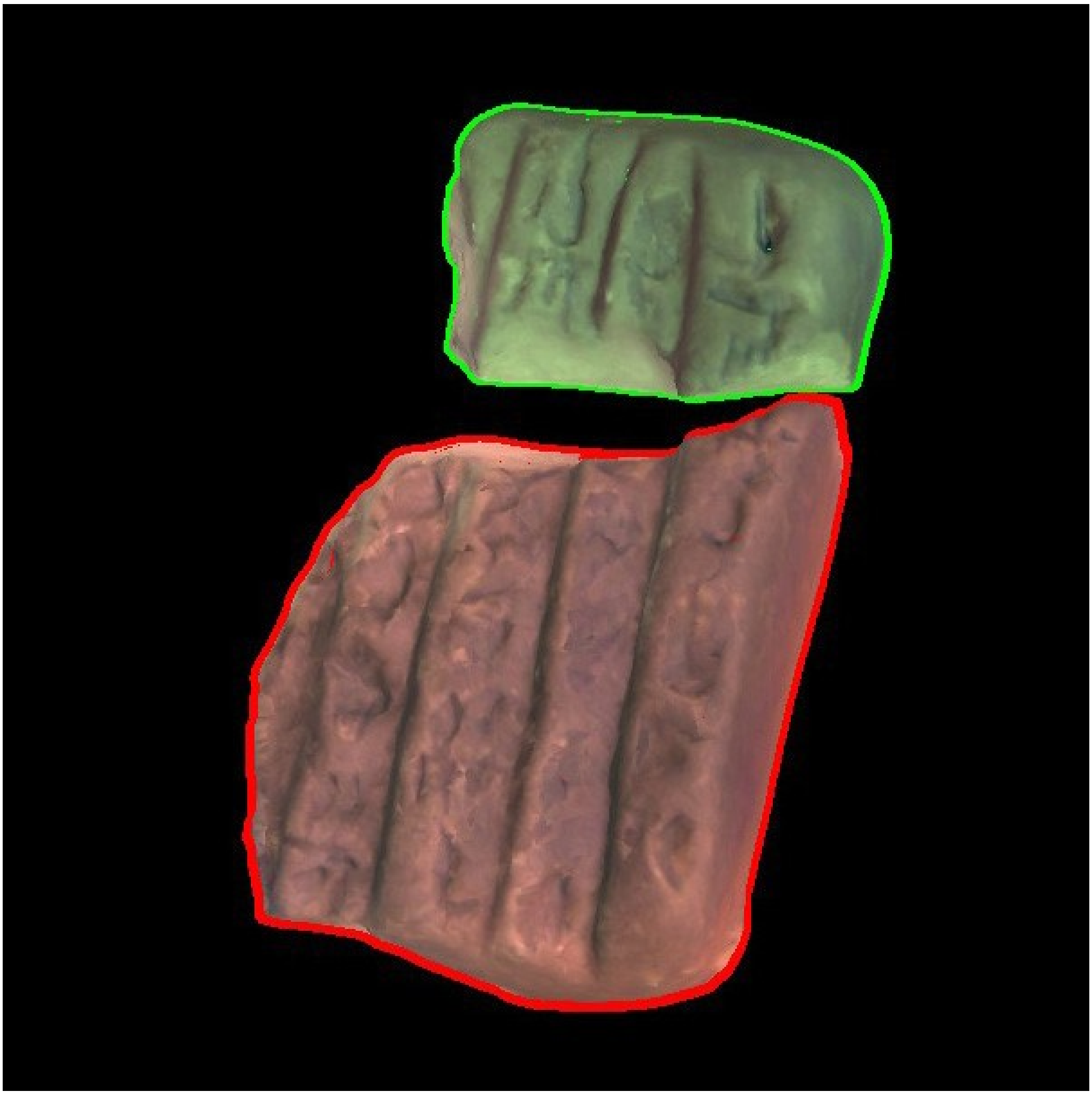


Figure 31: This screenshot shows the effect of the masked edge tool on fragments. The brightly coloured edges of the fragment can be clearly seen.

The purpose of the masked edge tool is twofold. Firstly, participants in previous experiments noted that it was difficult to match two fragments together when their surface textures were so similar. The masked edge tool projects a brightly coloured edge around a fragment, making the exact edge shapes more visible to the user. In addition to this, it is intended that the thick line of the brightly coloured edge serves as a ‘buffer’ to temper the participant’s desire to continue trying to align fragments perfectly when they are already sure that the fragments fit together – a behaviour observed in previous experiments.

Suggested Matches

The interface featured a panel that showed potential matches for the currently selected fragment. The number of times that a fragment had been suggested by other users (or by algorithms) was highlighted, with higher numbers indicating increased confidence in the match being correct. For the purpose of the experiments, these numbers were restored to pre-test defaults at the beginning of each task so that no cumulative effect would be observed.

Notes

The ability to add general notes about a particular fragment was added after participants in previous experiments were observed leaving post-it notes for other participants in asynchronous collaboration tasks. The notes may serve as an aide-mémoire to the participant, or as a guide to future participants. For the purpose of the experiments, the contents of the notes were restored to pre-test defaults at the beginning of each task so that no cumulative effects would be observed.

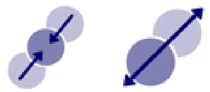
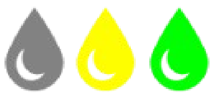
4.5.2 Keyboard Shortcuts

The following table shows the keyboard shortcuts that are associated with interface actions.

Key	Action
Q+A W+S E+D	**Rotate** Rotates the fragment that the user is working on around it's X, Y, or Z axis.
B	**Bring-to-Front** Moves a fragment that the user is working with right up to the front of the screen, so that it can be observed more closely.
G	**Ghost-Mode** Makes the fragment that the user is working with semi-transparent.
1	**Disable grouping** Removes the current fragment from any groups.
23 45 67 8	**Enable Grouping** Group fragments together for easier sorting. Each number key will place the currently selected fragment into a different group. Fragments in groups change colour to indicate the group they are in. If the glue mode is active, the joined fragments will rotate and move as a single object (as though they were glued together). If glue mode is not active, the fragments will move independently of each other.
MM	**Masked Edges** This feature puts a border around the fragment that the user is working on, so that the edges are more clearly defined.
C	**Camera move** Holding down the this key allows the user to revolve the camera left and right around the fragments.

4.5.3 On Screen Buttons

The following table shows the on-screen buttons that are associated with interface actions.

	**Glue Mode** This button works alongside the grouping function to make fragments act as though they are glued together. Groups of fragments will move together as one when glue mode is active (the arrows on the button point inwards). The fragments will move independently of each other when glue mode is not active (the arrows on the button point outwards).
	**Redo/Undo** These buttons let you cycle backwards and forwards through your actions, so that you can undo any mistakes you make while moving or rotating fragments.
	**Notes** This button actives and deactivates the note panels on the side of the screen, which can be used to view or make notes about a particular fragment, and to see if anyone has suggested that the current fragment joins to another fragment in the database.
	**Suggest Match** If a user believes that two fragments should be joined together, they put them in a group and use the suggest match feature to mark them as potential matches.
	**Grouping** These buttons are only present on touch screen devices. They allow you to place fragments into different groups (as with keyboard shortcut keys 1-8). To ungroup a fragment, use the grey button.

4.5.4 Node.js server

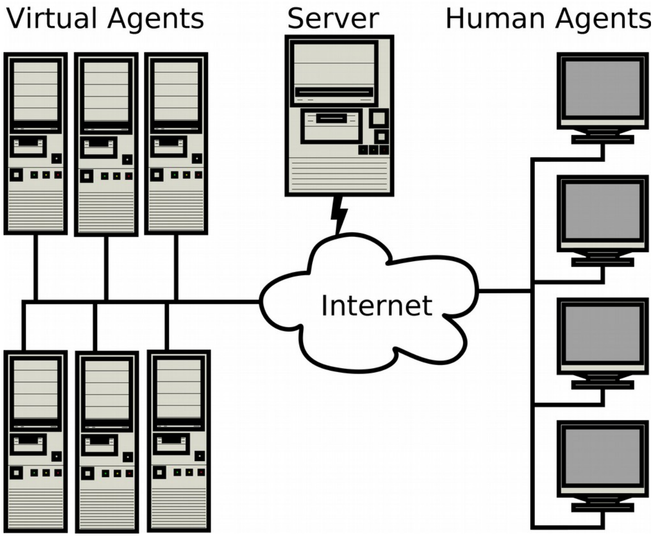


Figure 32: Diagram showing the structure of the server/client system for the reconstruction system. Note that virtual and human agents connect to the same server, and may even be collocated on the same physical machine.

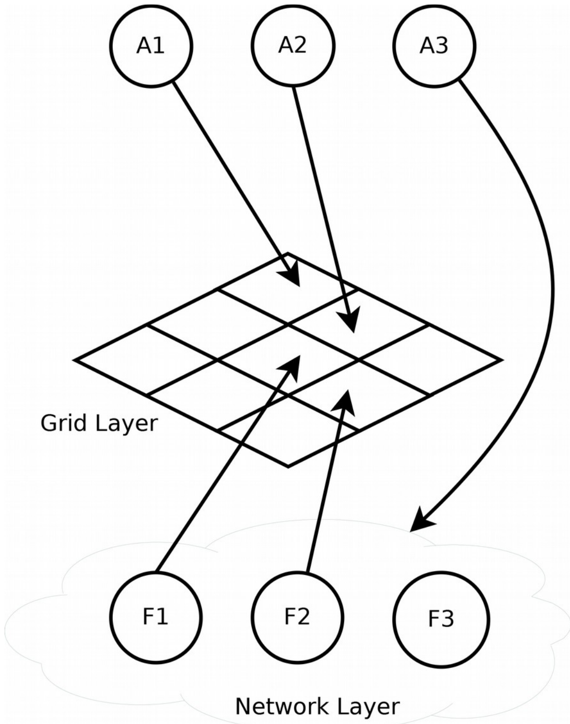


Figure 33: Diagram illustrating the interaction between agents (A) and fragments (F) in the virtual system. Fragments may exist on the grid (as A1 and A2 are shown) or may not be placed. Agents may access the grid to retrieve clustering information, or may access the fragment directly (as in the F3, A3 interaction).

The nodejs server also acts as a web-server, transmitting the front end interface and any fragment model files to connected clients. Combining the file and socket servers onto a single system prevents web browsers and anti-virus software from perceiving the normal operation of the interface as a potential cross-site scripting attack.

4.5.5 Agent framework

The agent framework is based in Python, with parallel processing support. Threading and FIFO (First in First Out) queue systems have been implemented to add both synchronous and asynchronous support for socket communication. A base Agent class is provided that supports a life-timer and also a throttle to control execution speed. The system has the facility for new virtual agents to be automatically spawned on an appropriate local or distributed processing node, and these agents can be given the power to spawn new agents of their own as required. The life-timer of an Agent can be adjusted at any point, extending the life of successful Agents, and reducing the life expectancy of agents that make poor choices. Figure 34 shows an example flowchart for a simple “clustering agent”, which clusters together fragments with similar properties on the grid.

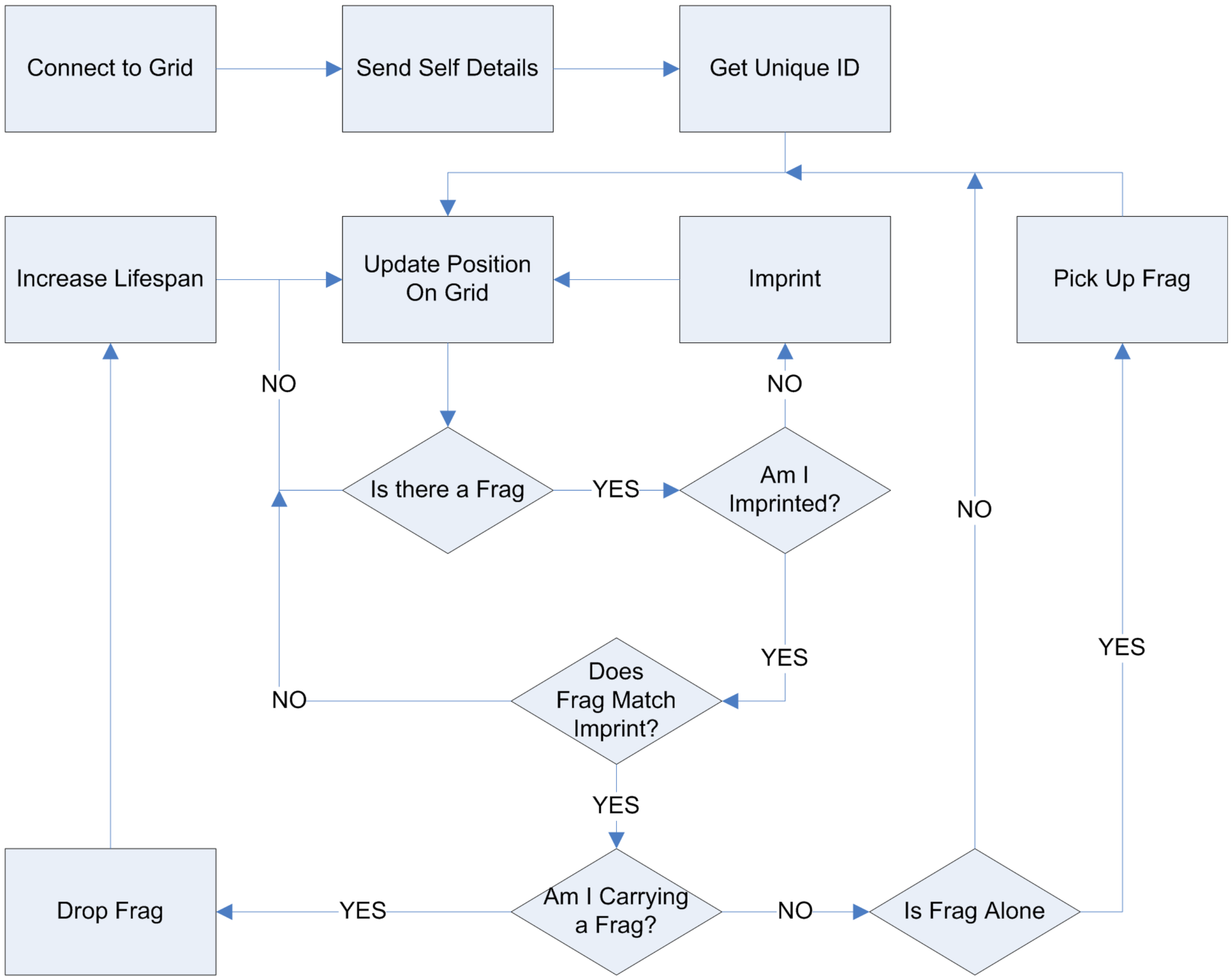


Figure 34: This chart shows the flowchart for a simple agent that operates on the grid, clustering similar fragments together. The agent begins by connecting to the grid and registering itself as a unique entity, before positioning itself and then imprinting on the first fragment that it finds. If the agent fails to find other fragments to cluster together, it eventually dies.

4.5.6 An example of agent creation

The following example creates a new agent that prints out it's life expectancy, and then dies after 3 ticks. Note that in a multiprocessing environment, the text output would be suppressed, but in a single instance, the text will be output to the interpreter. The start () and stop () functions of the Agent class start and stop the execution of the agent. An agent that has been stopped will not age (it's lifetime will not reduce) until it is started again.

```
from agent import Agent
class My_Agent (Agent):
 def main (self):
 print "I have ", self.LIFE, " life left"

a = My_Agent (life=3)
a.start ()
```

4.5.7 An example of communication with the server:

All agents created with the agent class can communicate with the Node.js server server from within the main () function by using self.ul.send () and self.ul.recv () functions. It is also possible to access the server without an Agent, using the Uplink class as shown below.

```
from uplink import Uplink
ul = Uplink (hn = "localhost", pn = 8000, pt = 10)
ul.connect ()

for i in range (100):
 ul.send ("rotate","fragment.js",1.2,1.2,1.2)
 incoming = ul.recv ()
 if incoming:
 print incoming
```

The ul.send () and ul.recv () functions are tailored to the transmission of positional data, with the send () function accepting an action, fragment id, and x,y,z data. Differently formatted messages can also be transmitted and received using the ul.sendraw () and ul.recvraw () functions.

4.6 Summary

This chapter documents initial experimentation and practical research that explore and develop technologies useful in the field of cuneiform reconstruction. In particular, these experiments have resulted in a series of modifications that make high resolution 3D printing possible on a domestic 3D printer, and suggest a portable scanning solution for the high resolution capture of cuneiform fragment models. This means that users may be able to use 3D printed tablet fragments to aid in the physical reconstruction process. 3D printed fragments allow the user to take advantage of the increased dexterity and tactile feedback afforded by the real world without being hindered by geographical or handling constraints associated with genuine cuneiform fragments.

In the same vein, acquisition technologies have been explored, and it has been shown that capture with a level of detail greater than that required to identify cuneiform markings can be achieved using relatively inexpensive scanning equipment. With this in mind, the possibility of in-the-field capture becomes more practical, although the speed and level of automation of the scanning process must be considered in cases where bulk scanning is required.

The chapter also shows the early photogrammetric analysis of complete cuneiform tablets in the CDLI database, which contributes to the understanding of the reconstruction process by providing a likely template that completed reconstructions can be measured against. This contribution and the algorithm which it relies upon could be transferred to other fields of fragment reconstruction where the exact end-point of the reconstruction process is unclear.

Finally, the chapter shows the development of the virtual framework and tools for the manipulation of fragments in 3D, which are tested in chapter 5 and are shown to contribute greatly to the reconstruction process.

CHAPTER 5: EXPERIMENTS

Previous chapters have presented the results of ancillary studies and shown that the cuneiform reconstruction problem is one of human ability as well as technological advancement. In order to solve this problem, a deep understanding of human behaviour and interaction during the reconstruction process is needed. This chapter presents two experiments which contribute to the understanding of the process of cuneiform reconstruction. The first experiment was designed to discover the behaviours and strategies employed during the process of cuneiform reconstruction. The results from this experiment were used to develop novel tools designed to improve the virtual reconstruction process (as described in chapter 4.5). The second experiment described here shows that the package of tools developed were highly effective at improving the performance of participants during reconstruction tasks.

5.1 Experiment One: Observed Behaviours and Strategies

5.1.1 Introduction

With the exception of Ch'ng et al. (2013) which suggests that a solution to the problems associated with cuneiform reconstruction may exist in the field of complexity science, there is currently no published research specific to cuneiform reconstruction strategies or behaviours. The goal of this experiment was to determine the basic techniques employed by participants to join together and or discard clay fragments in both the real and virtual world.

5.1.2 Equipment

For this experiment, a Vizard based virtual interface was configured to accept mouse and keyboard input to control the position and rotation of fragments in virtual space. The application also supported stereoscopic 3D visualization using an interlaced field pattern and polarized glasses. A computer with an AMD Phenom II x4 955 processor, 8Gb of RAM, and an Nvidia GTX 560i graphics card was used for each test. A generic 105 key QWERTY keyboard and a 3 button optical mouse with scroll wheel were connected as input devices, and an LG Cinema 3D Monitor (D2342P) was used for both 2D and 3D output.

Five sets of clay tablet fragments were scanned using a NextEngine HD 3D scanner. Although the David scanner was available for use, it was not possible to automate the scanning of each fragment without construction of a new turntable. The NextEngine scanner was chosen because the fragments could be scanned without frequent supervision and manual processing. Each set contained between 6-8 fragments which were scanned in at medium resolution (at 2.5k sample points per inch), with each model containing approximately 1.5 million vertices. The resulting models were decimated to reduce the vertex count to approximately 30 thousand vertices and were then imported into a custom made virtual 3D environment.

5.1.3 Methodology

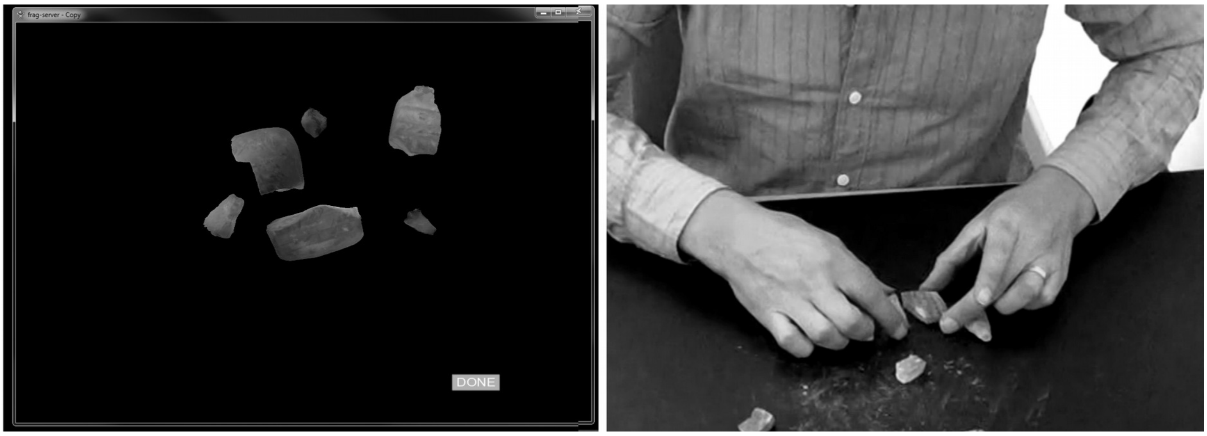


Figure 35: Screenshot showing virtual reconstruction task on the left, in contrast to a physical reconstruction task on the right.

Pilot studies were carried out to determine appropriate time limits for reconstruction tasks in the virtual and physical environments during each experiment. From these pilot studies it was determined that a time limit of 12 minutes was appropriate for virtual tasks. Each participant in the study was isolated for the duration of the experiment in the Chowen Prototyping Hall at the University of Birmingham. Participants were presented with a series of tasks that involved three methods of reconstruction:

Physical reconstruction

The participant was asked to reconstruct physical tablets from a collection or collections of fragments. Participants were informed at the beginning of each task that the collection of fragments they were presented with may be pieces from one tablet, more than one tablet, or may not fit together at all. The collections were sorted so that they contained the fragments of a complete tablet and either zero or more superfluous fragments. The purpose of this task was to provide baseline values for current reconstruction methods, and explore the effect of superfluous fragments on the manual reconstruction process.

Virtual reconstruction

Participants were presented with the equivalent reconstruction tasks of physical participants, but were given virtual 3D fragments rather than their real-world counterparts.

Stereoscopic virtual reconstruction

Participants were shown virtual fragments on a 3D monitor, and asked to perform the same reconstruction tasks as described above. This test restores a sense of depth perception to the participant, but still requires manipulation of 3D objects using standard input devices. This separates the effects of the lost depth perception from the effects of remote object manipulation using a keyboard and mouse.

Participants were also asked to reconstruct sets that contained either 2 superfluous fragments, or a number of superfluous fragments equal to the number of valid fragments (N) in the set. These tasks were referred to as N+2 and 2N respectively. In all cases, the time taken to complete the task and the accuracy of the completed tablet were recorded, as was the time to make the 1st and 2nd join. For virtual tasks, the physical operations (rotate, move) used to achieve the end result were recorded in a log of participant interactions during each test. At the completion of each task, the participant was asked a series of questions to elicit qualitative feedback. The environment used in the experiments was consistent, with physical surfaces coloured black to match the background colour of the screen used in the virtual tasks. Identical input and output devices were used for all virtual tasks, and instructions were provided in a script. Information about the controls for the virtual system were provided on a printed sheet next to the computer, which the participant was instructed to read before the test began. The sheet remained in place next to the computer for the duration of the experiment.

5.1.4 Participants

After consideration from multiple sources (Guest, 2006; Mason, 2010; Schmettow, 2012), it was decided that as the current study represented a precursor to a larger investigation and involved both qualitative and quantitative aspects, sufficient information to determine the direction of future work could be obtained with a relatively small number of participants. In total, 15 participants were performed the experiments, 8 of which were male and 7 were female. The mean age of participants was 32 years, with the youngest participant being aged 24 and the oldest age was 41.

5.1.5 Results

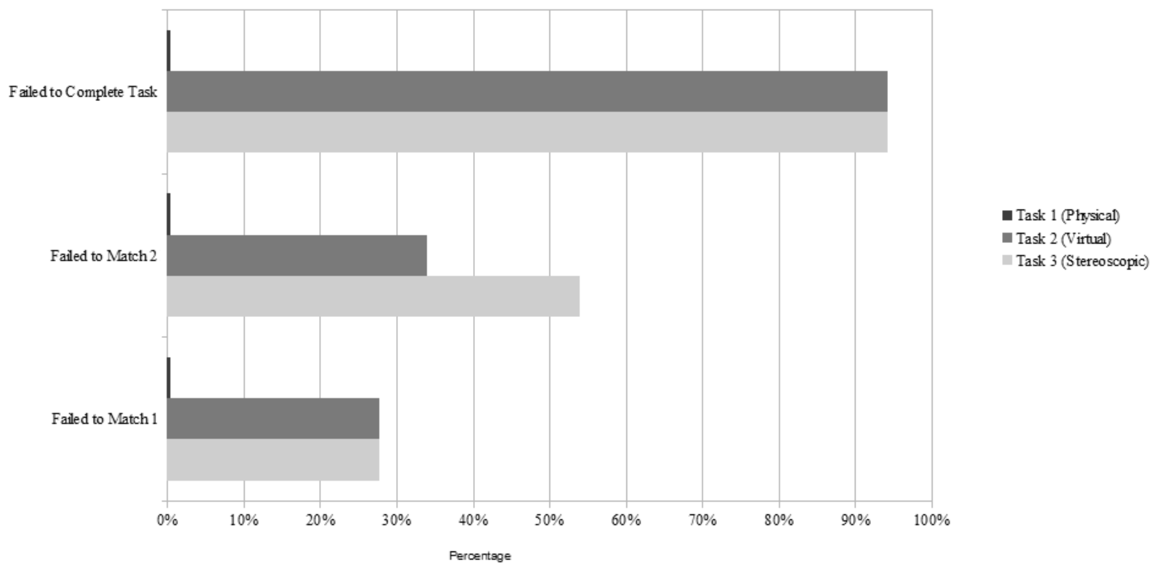


Figure 36: Figure showing percentage of participants unable to reach experimental milestones for each task.

All participants in the first test group were able to reconstruct the physical fragments into complete tablets well within the allotted time. The fastest join (i.e. the time to join the first two fragments together) was made within 5 seconds with the average time to the first join being 34.6 seconds. The average time between the first and second match was 32 seconds. The fastest participant completed the entire process within 65 seconds. No participant took more than 5 minutes and 49 seconds to reconstruct the tablet from the set of fragments that they were given. The interaction methods employed by participants fell into two broad categories: Methodical and Selective. Methodical interactions involved a “brute-force” approach to the reconstruction process, comparing fragments systematically and then retaining those pieces that join together. Selective interactions were more discriminating, involving careful observation of the fragments before choosing those that were likely to form a cogent pair. It was observed that participants favoured a particular method of interaction, and did not tend to change their method. It was also observed that the manual manipulation of fragments was very free, with multiple simultaneous operations. It was not unusual for rotation and movement operations to be carried out in both hands at the same time.

The initial freedom of motion became compromised as the number of fragments being held increased, so that participants were forced to discard the collections that they were holding in order to manipulate only relevant pieces. This became problematic as the reconstructed tablets neared completion. Several participants commented that glue or tape would have been helpful during the reconstruction process. Contrarily, the deliberate exclusion of simulated gravity from the virtual environment means that holding fragments in position is not an issue, although some participants noted that a method of grouping individual fragments into a single object would have made manipulation easier. Unfortunately, the restrictions of a virtual interface using standard equipment currently prevent the fluid ambidextrous manipulation of multiple fragments. When using a keyboard and mouse, the participant is restricted to sequential actions on a single fragment, which in turn increases the time required to manipulate fragments into the desired position.

Performance in the virtual tasks was significantly lower than in the physical, with only one of the participants managing to reconstruct a complete tablet before the end of the 12 minute session. However, 11 of the 15 of participants were able to make at least one successful join, with the fastest participant taking 27 seconds to make a connection. Another participant had the shortest inter-match time (the time between a participant making the first and second join), taking just 33 seconds to find the second join.

With the sequential nature of virtual manipulation (where users are restricted by the interface into performing actions on only one fragment at a time), almost 75% of the actions carried out by the participant are rotations, which typically occur before a participant moves fragments together.

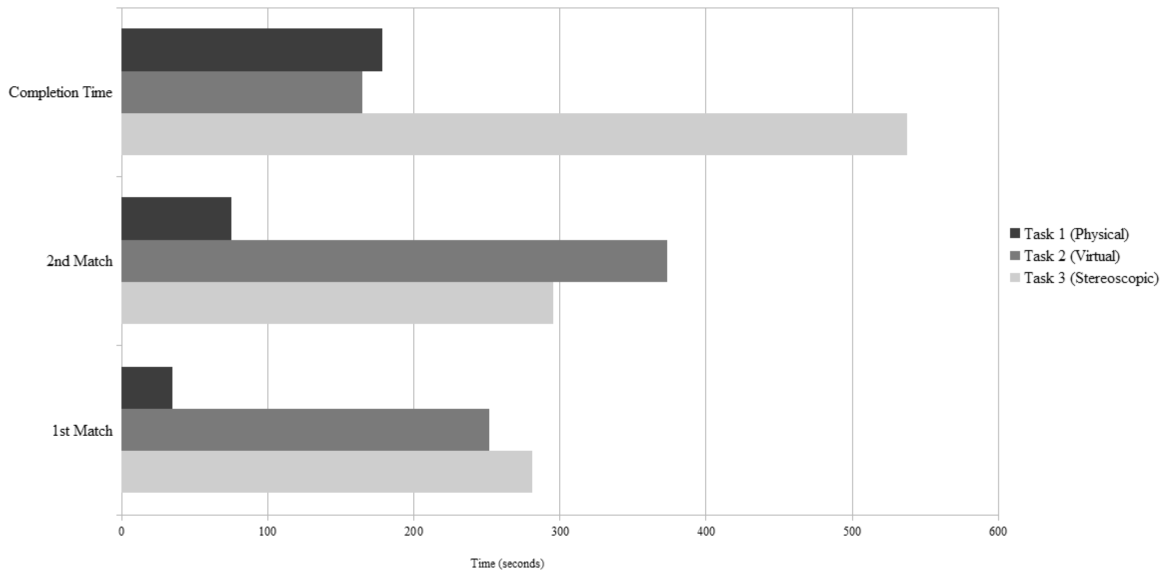


Figure 37: Figure showing the mean 1st match, 2nd match and completion time for each task.

The participant interactions were classified so that participants who were able to make at least two matches in the virtual system were deemed to be successful, while those who made fewer than two joins were classed as unsuccessful. Successful participants typically rotated fragments less, with an average of approximately 72%, ranging between 56% and 83%` rotations. In contrast, 77% of the interactions made by unsuccessful participants were rotations, ranging between 70% and 92%.

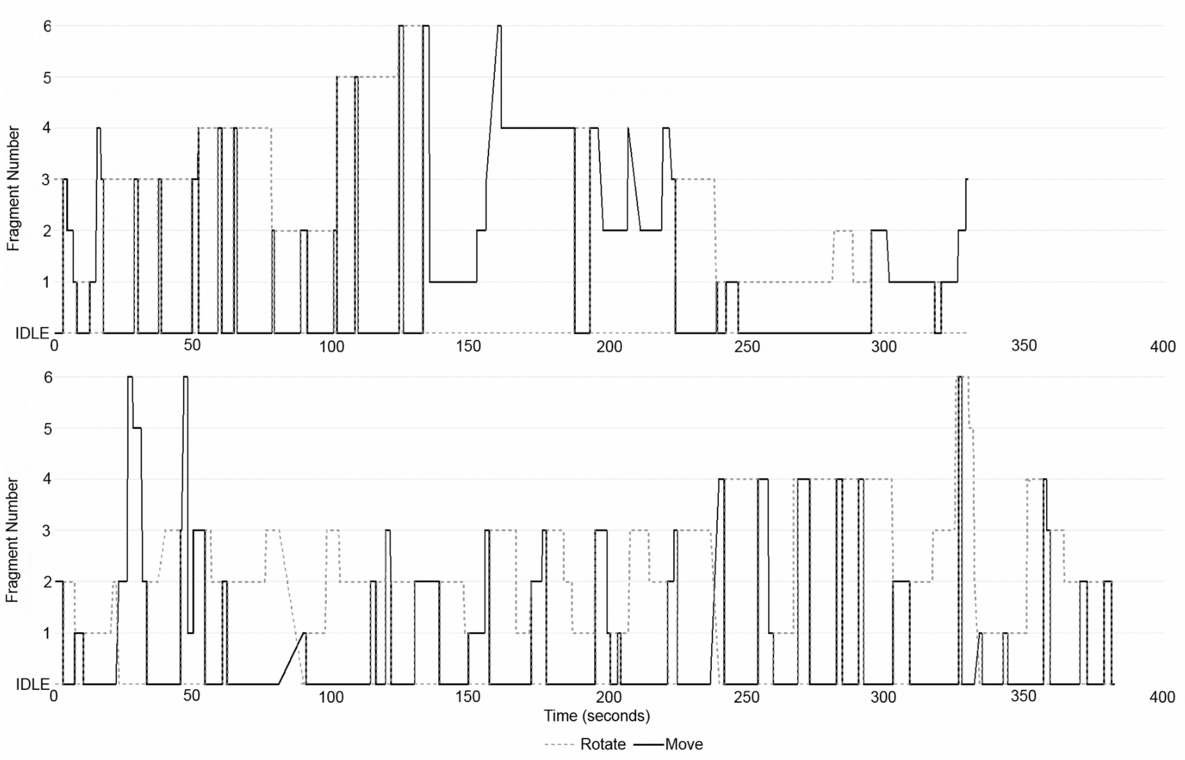


Figure 38: Figure showing the rotation and movement actions of unsuccessful participants when using the virtual reconstruction system.

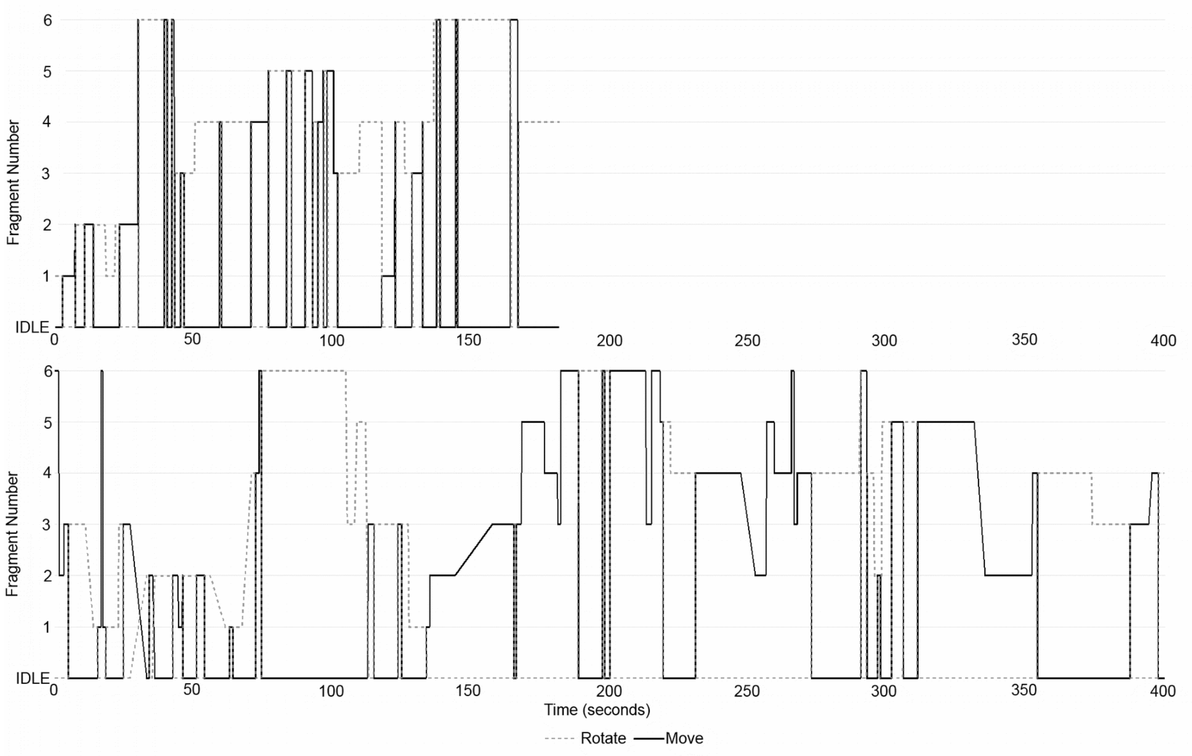


Figure 39: Figure showing the rotation and movement actions of successful participants when using the virtual reconstruction system.

If a participant aligns one fragment so that the edge appears to join with another fragment, the participant will move the fragments together and attempt a close fit. Pieces that do not match will typically be moved away from the target piece and discarded. This method of virtual reconstruction is reminiscent of the selective strategy employed by some participants in the manual reconstruction experiments. It is possible that the speed reduction encountered when using the virtual interface makes a brute-force, methodical approach to the joining process too laborious for users to focus on.

In common with physical strategy, 14 of the 15 participants began their digital reconstruction tasks by manipulating one of the larger fragments in the set, with 6 participants choosing the largest available fragment regardless of its position on screen. This mirrors observational evidence from the physical tests and also the feedback from several users on their individual reconstruction strategies.

The size of the first fragment chosen by the user did not directly affect the speed at which the participants made matches, although it may be useful to consider this preference for starting when designing a virtual system that can automatically suggest fragments to users. In the majority of these cases, the users will be looking for a smaller fragment than the one they currently hold.

Graphing the points of interaction within the virtual space reveals that unsuccessful participants (those who made fewer than two joins in the virtual system) were more likely to pull fragments towards the camera to enlarge them, while successful participants (those who made two or more joins in the virtual system) spent more time interacting with fragments at their original location.

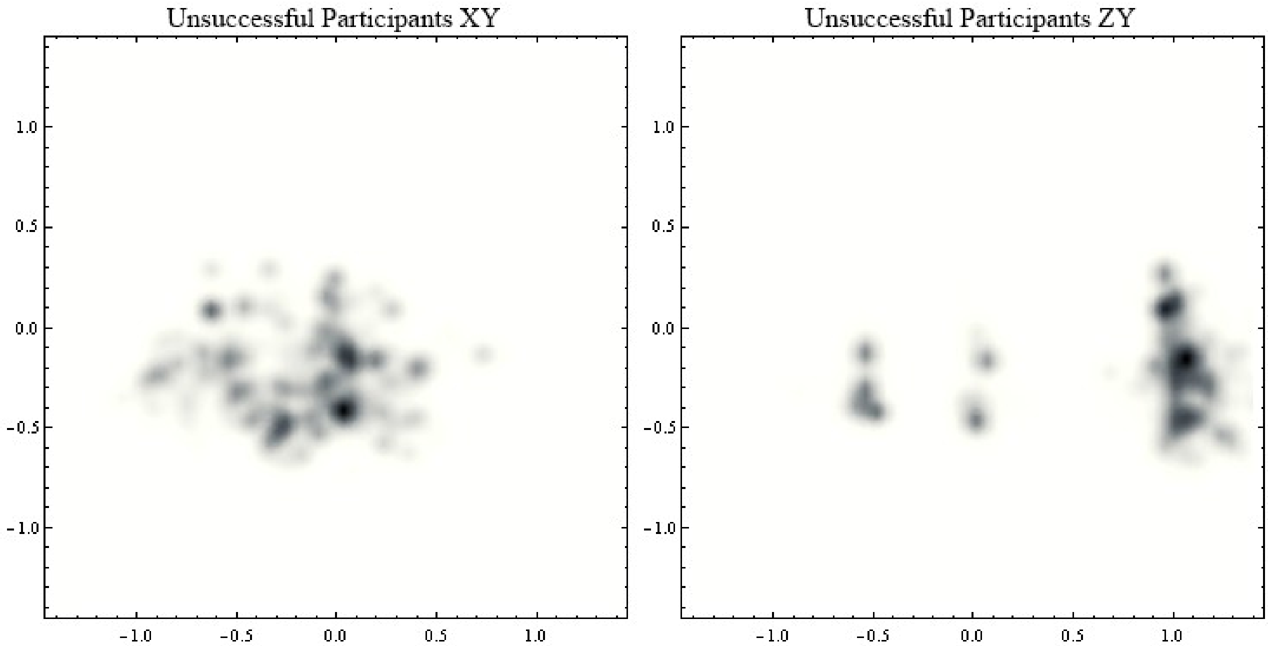


Figure 40: Interaction map showing the average frequency of fragment interaction in 3D space for unsuccessful participants. The left hand Figure represents a "screen view", whilst the right hand Figure shows the depth of fragments within the space.

These interaction maps in Figures 40 and 41 show a front (XY) and side (ZY) view of the virtual space, with the areas of most activity being shaded darker. If we examine these Figures, we can see that the most noticeable clusters of activity are at depth 1 in the Z axis, which is the default starting position that fragments are placed on the screen.

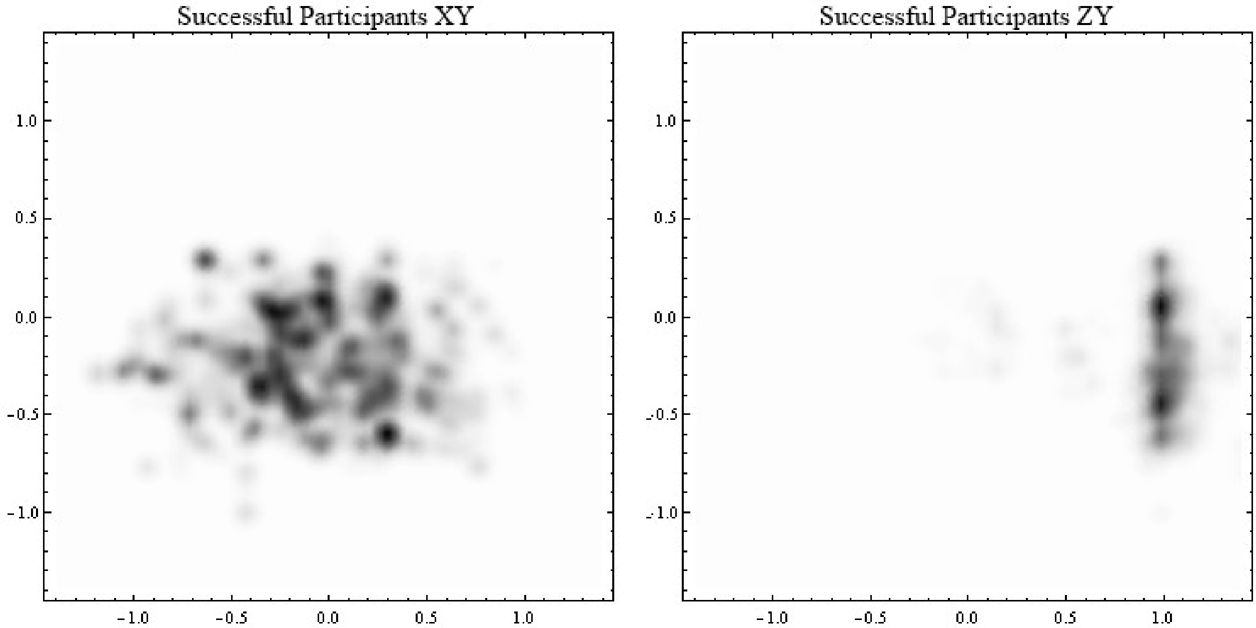


Figure 41: Interaction map showing the average frequency of fragment interaction in 3D space for successful participants. The left hand Figure represents a "screen view", whilst the right hand Figure shows the depth of fragments within the space.

This activity is present for both successful and unsuccessful participants. The Figure of the unsuccessful participants also shows clusters of activity at depth 0 and at -0.5 which indicates that the fragments have been moved towards the camera. The disparity between the interactions of the successful and unsuccessful participants is more pronounced when viewed in 3D.

Figure 42 is a 3D representation of this spatial interaction information and shows the sparse interaction patterns of the unsuccessful participants, with isolated areas of activity towards the default fragment depth of 1, and the zero point of the Figure. In contrast, the successful participants whose activities are illustrated in Figure 43 show a greater level of activity at the default fragment depth, whilst very little activity occurs in other areas of the virtual space.

As would be expected, the introduction of superfluous fragments appears to increase the time that participants need to make a match, with the minimum completion time increasing as the number of spurious fragments increases. This is reflected in the results from the physical tasks as shown in Figure 44.

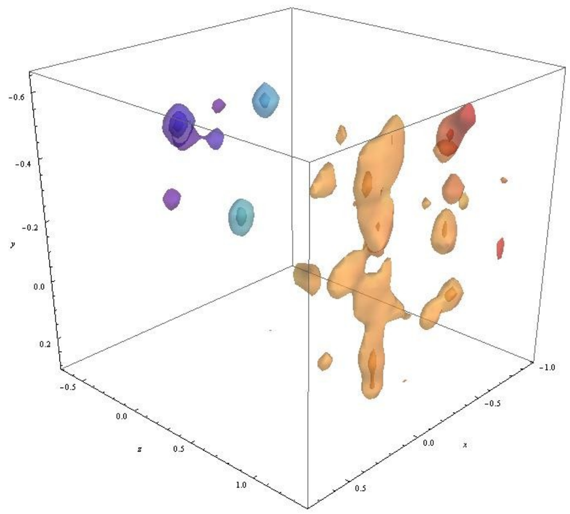


Figure 42: Figure showing the interaction patterns of unsuccessful participants in the virtual space.

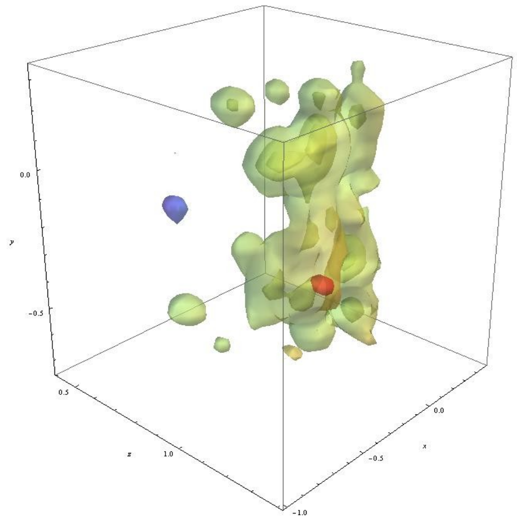


Figure 43: Figure showing the interaction patterns of successful participants in the virtual space.

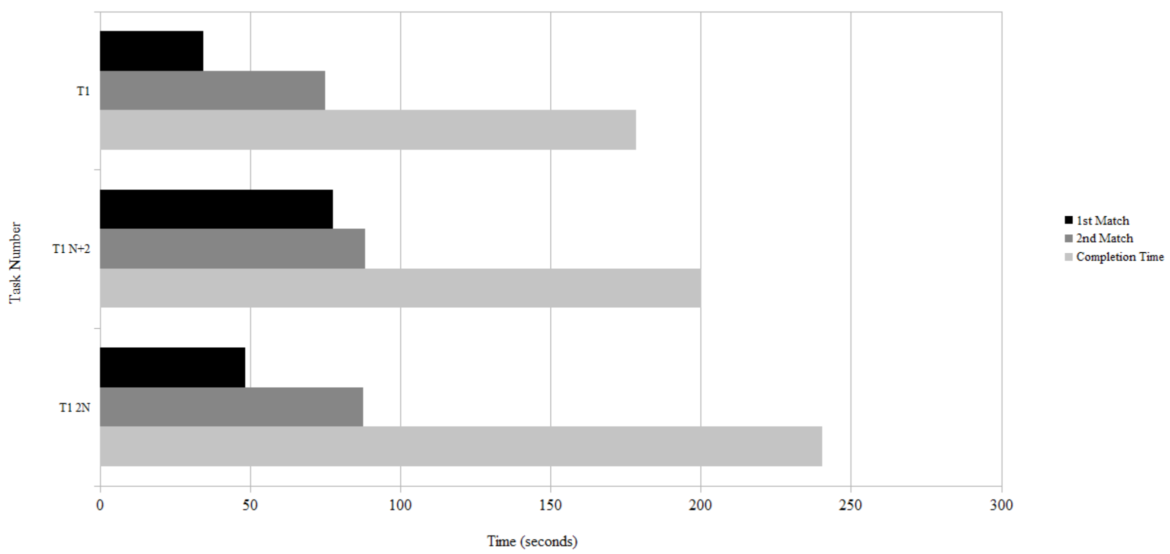


Figure 44: The effect of additional fragments on reconstruction time for participants in task 1.

5.2 Experiment Two: Assessment of Virtual Tools

5.2.1 Introduction

The primary goal of the experiment described here was to assess the effectiveness of tools developed to facilitate cuneiform reconstruction in the virtual world. Additionally, the effect of cognitive style on perceived and actual reconstruction performance was also examined.

5.2.2 Equipment

Four sets of fragments were 3D scanned using a NextEngine HD 3D scanner at medium quality (equivalent to approximately 2.5k sample points per inch), with each set containing either five or six fragments that fitted together to form a complete tablet. Each fragment was decimated, reducing its file size and its overall vertex count to less than 10k vertices. The purpose of decimation was to improve load times for the fragments, and decrease the amount of processing required by the 3D renderer on the test computers. The fragments were loaded into a specially designed web-based virtual environment that leveraged ThreeJS at the client end to visualize the fragments and implement the custom tools described below. The server side of the system relied on NodeJS/MySQL to serve fragments to the clients and to log their actions.

5.2.3 Methodology

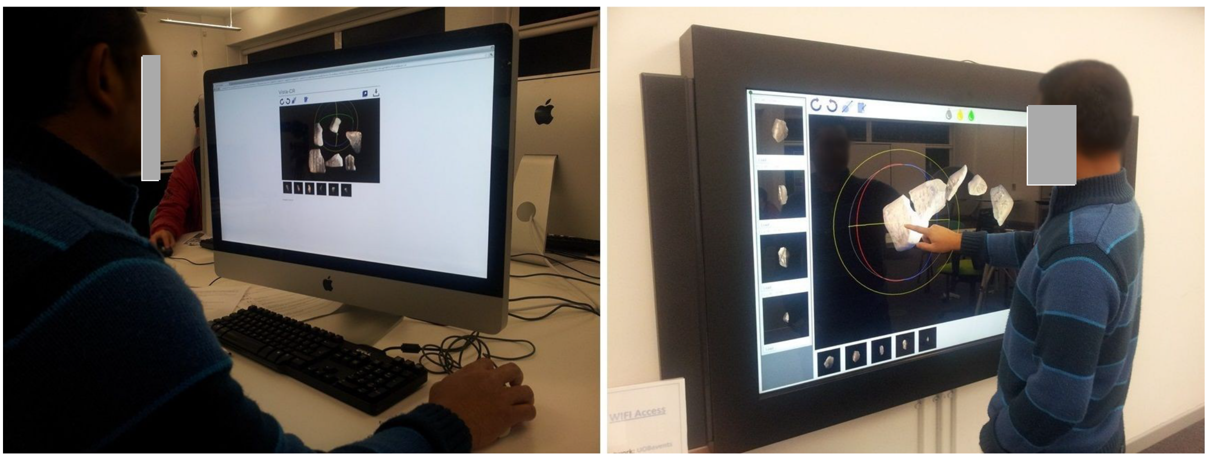


Figure 45: Photographs of a participant working with fragments during the control (left) and touchscreen (right) tasks of the experiment.

Each participant was asked to participate in four tasks. In each of the tasks the participant was asked to match together fragments of cuneiform tablets in a virtual 3D environment, while the interface presented to the participant was varied. The order of the tasks was varied for each participant, and the set of fragments presented during each task was also varied to ensure disassociation between fragment sets and individual tasks. The four tasks were:

Control Task

This task was configured to use only the mouse to control the virtual system, and was used to establish a base level against which all other tasks were measured. There were no visual cues or tools active during the experiment. The interactions and the number of matches made by the participant were logged by the system. The duration of this task was 5 minutes, after which the user was allowed an additional minute to make any final matches.

Interface Task

The Interface task was used to test the effects of the custom interface tools (Bring-to-Front, Keyboard-Rotate) and visualization (ghosting, fragment outlining, and surface re-texturing) effects on the reconstruction process. The interactions and the number of matches made by the participant were logged by the system. The duration of this task was 5 minutes, after which the user was allowed an additional minute to make any final matches.

Interaction Task

This task was designed to assess the value of notes left by other users within the virtual interface. The functionality of the interface tools in this task was identical to task 2. Notes were associated with individual fragments within the virtual system, and during this task these notes were displayed to the participant whenever they clicked on a fragment. The interactions and the number of matches made by the participant were logged by the system. The duration of this task was 10 minutes, after which the user was allowed an additional minute to make any final matches.

Touchscreen Task

This task replaced the keyboard and mouse with a touchscreen display, to assess the effect of direct vs. indirect manipulation of fragments. The functionality of the interface tools in this task was identical to task 3, with the exception that additional icons were added to the screen to mimic the functionality of keyboard shortcuts. A 64 inch wall mounted touchscreen was used for this task, to reduce the effects of obfuscation of the fragments by the user's finger, while still maintaining a suitable virtual workspace size. The interactions and the number of matches made by the participant were logged by the system. The duration of this task was 10 minutes, after which the user was allowed an additional minute to make any final matches.

5.2.4 Participants

The experiment consisted of 37 participants (18 female, 19 Male). The mean age of participants was 27.1 years, with a standard deviation of 10.6. The oldest participant was 73 years old, and the youngest was 18 years. All of the participants had either completed or were currently studying a university course. With regard to their expertise, 22 of the participants had an education in the arts, while the remaining 15 came from a science or engineering background. While all 37 participants successfully completed the tasks assigned to them, 10 of the participants did not successfully complete the SUS and TLX questionnaires for one or more of the tasks and were excluded from those calculations that involved TLX or SUS scoring.

Before the beginning of the experiment, participants were asked to complete a short demographics form and to complete an online variant of the GEFT (Group Embedded Figures Test). The purpose of the GEFT was to gain an objective measure of each participant's field dependence (FD) or field independence (FI), and their ability at solving geometric problems.

5.2.5 Results

Prediction of Performance Using GEFT

Since the GEFT score measures the ability to solve geometric problems (Demick et al. 2014; Hong et al. 2012; Keehner et al. 2006) it is not surprising that a significant (+0.35, using Pearson two-tailed) number of participants with a higher GEFT score also reported having a higher level of previous 3D problem solving experience. While GEFT scores had no significant effect on the overall cognitive load of the participants during the experiments (as measured using NASA TLX RAW), positive correlations were found between the participant's GEFT score their scoring of the experimental system using the System Usability Scale for experiments two and three (those experiments where the experimental tools were active and participants used a conventional keyboard and mouse). A possible positive correlation was also noted between the GEFT score and the SUS scores for the fourth experiment, although this was below the level set for statistical significance. Overall, participants with a higher GEFT score rated the experimental interface more highly than those without.

Interaction Performance

It was found that participants within the treated groups were able to interact with the fragments more frequently than those in the control groups (see figure 46). This means that participants using the reconstruction tools were able to engage more with the fragments more than participants without the additional tools over a given period of time. While the amount of increase is small (at 5% between the Control and Interface tasks), it does provide a definite indication that the reconstruction tools are facilitating interaction. A less significant increase in interaction (around 3%) was noted between the interaction and touchscreen tasks.

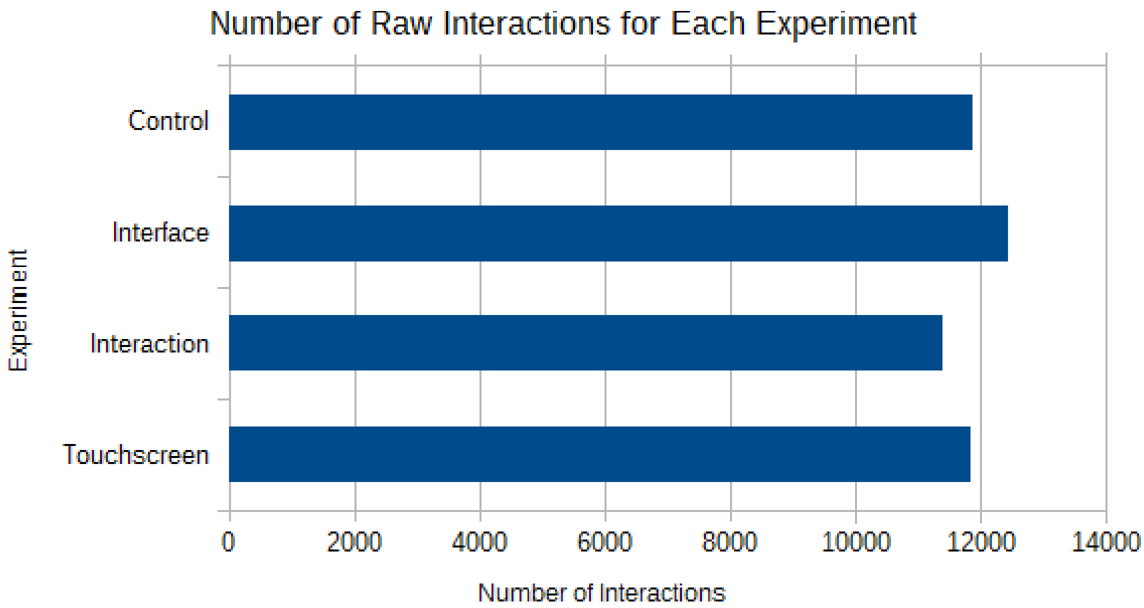


Figure 46: Number of interactions taking place during each experiment, normalized for time.

Suggested Matches Performance

It is clear from the number of matches made by participants that the reconstruction tools are affecting the reconstruction process in a positive way. In the control group, a total of 36 matches were made over the course of the experiment, two of which were duplicates (where a participant repeatedly matches the same two fragments). With the reconstruction tools active, the number of matches increased to 80 with a total of 10 duplicates, and the number of participants making matches during the experiment increased from 6 to 8. These results are illustrated in figure 47 (where the results for all users are displayed ordered by task) and figure 48 (where the results are broken down to display the performance of individual users in each of the tasks.

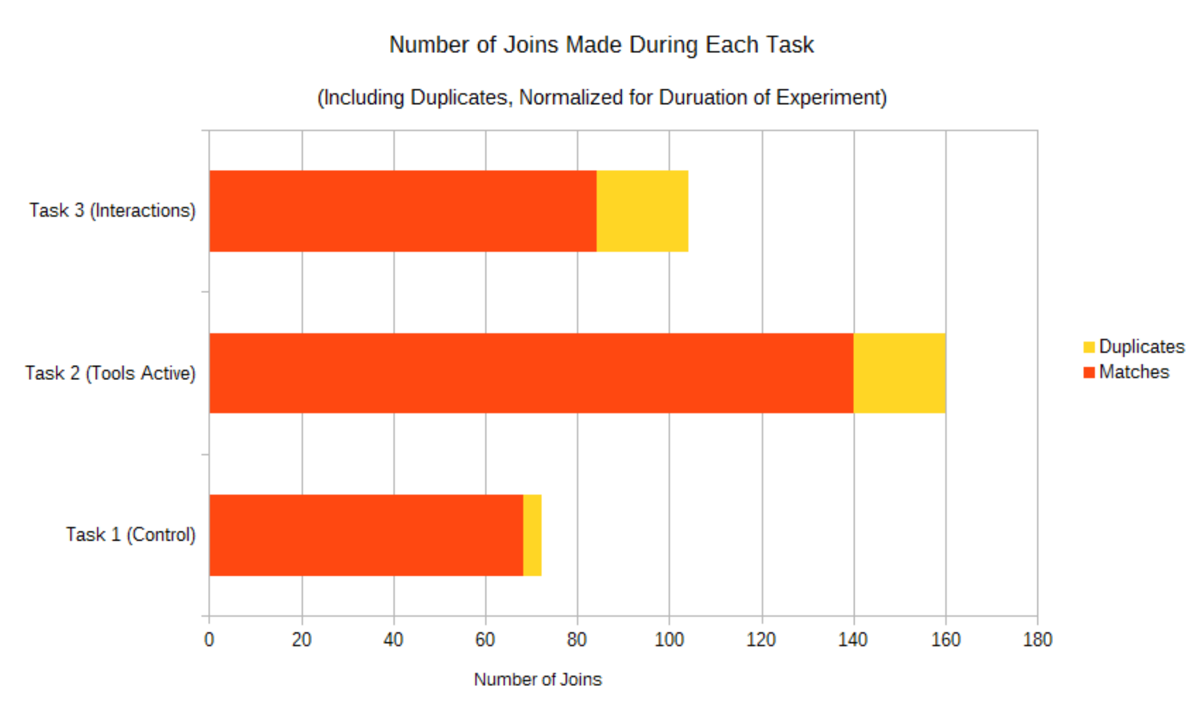


Figure 47: Number of joins with duplicates for the first three tasks, normalized for the duration of the experiment.

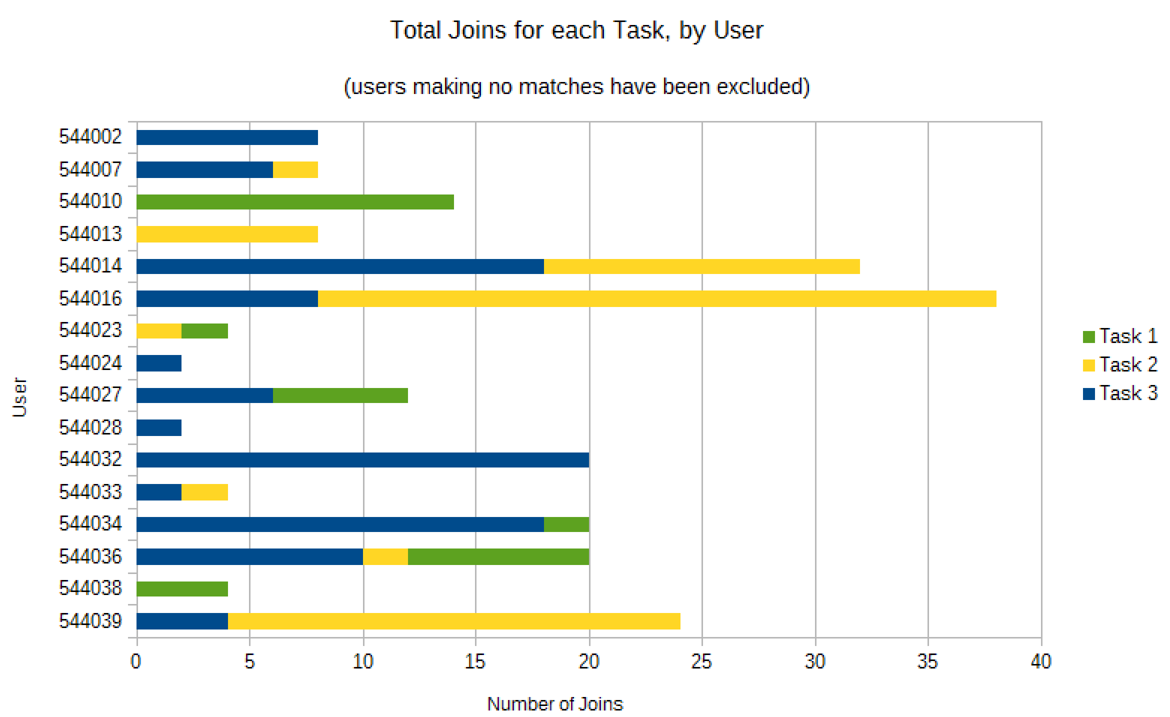


Figure 48: Figure showing the number of joins made by each user, for each task. Users who are not shown here did not make any matches.

5.3 Summary

This chapter documents two experiments that explored the process of fragment reconstruction in real and virtual worlds. Experiment one explored the actions of users during the reconstruction process, and revealed a number of strategies and behaviours that successful and unsuccessful participants made during their experiments. The results from this experiment were used to develop a set of novel tools that make the process of cuneiform reconstruction easier for participants to complete.

The second experiment tested the effectiveness of the novel tools on the process of fragment reconstruction. The results from this experiment show that the tools are extremely effective, doubling the rate at which joins are made between fragments and increasing the level of interaction between users and the reconstruction framework. This experiment also sought to find correlations between the demographic information of participants and their performance during the experiments, although there were few significant links found.

These experiments provide a contribution to knowledge in the field of cuneiform reconstruction methods, and also prove that the novel tools and framework developed as part of this thesis have a positive effect on the process of reconstruction.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

The previous chapter presents the methodology and results of an experiment to explore human behaviours and strategies observed during the reconstruction process. It also reports the results of a consequent experiment to test virtual tools designed to improve user performance during the reconstruction process. This chapter discusses these results, and explores their relevance with respect to the research questions raised at the beginning of this thesis.

6.1 Observations on the Current State of Technology

With regard to the issues surrounding the current state of technology and it's ability to support cuneiform reconstruction, there is sufficient evidence to suggest a generally positive case. From the perspective of 3D fragment capture, it can be seen the emergence of a number of low-cost technologies that produce virtual 3D models with a sufficient resolution for future scholars to explore, reconstruct, and parse the fragments with whatever technologies may exist to facilitate reconstruction. In fact, a long history of 3D scanning techniques can be established, showing that the field of contact-less geometric measurement has been active for well over 100 years (British Pathé, 1939; Gall, 1997; Massieu, 1860). The availability of new technology is not a hindering factor, although other obstacles to adoption may exist that parallel the slow uptake of photographic recording in the 19th century. Initial costs for equipment, and most recently, maintenance costs for the storage of data, limited technical expertise, and the sheer volume of data (Johnson et al., 2014; Rothenberg, 1995) may prevent the adoption of these new technologies until more parsimonious methods for their long term use can be determined(Gollins, 2009).

When considering visualisation of the 3D fragments, the story is less clear. The experiments described in the previous chapter show that lack of depth perception is perceived by users as a problem, but when given access to the depth information via 3D displays, their performance does not improve significantly (Lewis, Woolley, Ch’ng, & Gehlken, 2015). 3D interaction technology has not yet advanced sufficiently to produce a device capable of creating virtual representations that have the same interface properties as a physical object. The limited 3D visualisation systems, gesture controls, and haptic feedback devices available at this time are simply not able to fool our senses into believing that we are manipulating a real 3D object.

It is hard to ignore the emergence and continued advancement of 3D printing as a tool for visualisation and content delivery(Hornick & Roland, 2003; Ju, 2011), even though at this time the process of 3D printing still requires a certain amount of expertise and technical understanding for successful execution. Until recently, the 3D printer was used as a tool for rapid prototyping and product development, and for advanced manufacturing. Examples of this usage exist within the jewellery industry, in aerospace, and in prototyping labs where the unique properties of the 3D printer as a tool can streamline the process of manufacturing and facilitate the manufacture of objects that would not be possible using existing technology (Davidson, 2012). Internally supported aircraft wings are an example of this. An aircraft wing with an internal honeycomb structure is stronger and lighter than alternatives, but can only be manufactured using 3D printing technology. Herringbone gears and lost cast mouldings for metal are other a less obvious examples, where the process of manufacturing a particular item is simplified considerably by using a 3D printer.

In addition to these traditional uses for 3D printing, the lower cost and mainstream availability of FDM printers (spurred on by the emergence of the maker community) has ushered in a new paradigm for the technology: 3D printing is as a content delivery system. 3D printers connected to the internet and to archives of model data are capable of delivering content to users in just the same way that a phone screen or a conventional printer are capable of delivering content. Games manufacturers are beginning to make content available as printable models (Anusci, 2015), supermarkets are offering 3D body scanning services, and individuals are using 3D printing as a method of sharing and remixing existing sculptural content. There are many examples of this behaviour on 3D community sites like Thingiverse(Makerbot Industries, 2015). In the future, the delivery of cuneiform tablet fragments to users may present a viable method for reconstruction that bypasses the current limitations of a virtual interface. However, there are a number of issues still to resolve at this early stage, principally surrounding the speed and fidelity of delivered content. The quality of printing is still relatively low at the domestic end of the market, and printing speeds are too slow to facilitate on-demand printing. It is tempting to draw a parallel between 3D printing, and the now ubiquitous inkjet printer or the fax machine. In the period since the inception of these ordinary 2D printing devices, we have seen a move towards the paperless office(Haigh, 2006), with the advent of email, the tablet revolution, and ebook readers replacing the paper copies that were once produced by fax machines and laser printers. 3D printing currently occupies the same stage of development that paper printing occupied 20 years ago, where the paper copy was the most convenient interface to the information that a document contained. Until we find a visualisation technology that will allow us to view and interact with 3D content with the same tactility and ease we associate with a real world object (a 3D version of the ebook reader), we will be forced to either rely on physical object copies or accept the deficits of the interface we chose to work with. This document has shown, however, that interface deficits not prevent the successful reconstruction of cuneiform fragments. Although it is clear that virtual objects are not as effective as physical objects for reconstruction tasks, the interface tools developed in this project have led to a huge increase in the amount of matches suggested during the experiments, with some users completing the virtual reconstruction tasks well within the time allotted for the experiment.

6.2 Analysis of Observed Behaviours and Strategies

Early experiments revealed a number of features that could be used to improve the virtual reconstruction process. Participants identified several physical attributes that they felt were important to the reconstruction process, including the surface markings and colour of a fragment. The smoothness of fragment surface was also identified as allowing participants to distinguish sign areas and blank surface areas from obviously broken edges. Participants commented that the size of the fragments was important, with larger fragments being used as anchor points for testing smaller fragments against. This was also shown in the analysis of the logs of initial interaction with fragment sizes from the virtual environment. Virtually pre-sorting larger collections of fragments by these features may improve efficiency of reconstruction. This technique has seen some success in the field of fresco reconstruction(Brown et al., 2008, 2010; Funkhouser et al., 2011), and a virtual system to suggest fragments based on these features is the next logical step.

Many subjects stated that the lack of haptic (tactile) feedback was an issue during the virtual reconstruction process, and the lack of depth perception (leading to problems with object scaling) was also mentioned by multiple users (see Appendix B).

While no technology currently exists to completely restore the sense of tactility to the virtual world, it may be possible to provide an audio or visual feedback system that provides feedback on the closeness of fit between multiple fragments. One example of such a system might be a border around the visible fragment that becomes more opaque as the closeness of fit between the fragments increases. However, the computational power required to perform accurate collision detection of complex models in real-time is very high, and may limit the technology that a reconstruction interface runs on. While accurate tactility may currently be impossible to implement in the virtual world, it is a less complex issue in the real world. Additive manufacturing techniques could be used to provide a physical copy of fragments that appear to join in the virtual system. These printed fragments could then be used to make a definitive decision on the validity of a proposed join. More extensive use of additive printing technology could also be considered so that staff with limited training can carry out multiple fitting operations concurrently. Replica parts are low value and replaceable, having no special handling requirements or storage considerations.

Returning to the issue of inadequate perception, while it was found that the use of binocular 3D subjectively increased the effectiveness of the virtual reconstruction environment, it produced no measurable positive effect to the success of the reconstruction process, and had negative associations with the availability of the technology and the increased eye fatigue caused by convergence/fixed-focus(Bang et al., 2014; Schild et al., 2012; Yu et al., 2012). One participant was unable to work with the 3D screen despite having no binocular vision defects. Several participants claimed to feel more able to perform the task when working with stereoscopic 3D models, but ultimately performed no better than those working with normal screens. In measured terms, fewer participants were able to make a second join when using stereoscopic 3D within the allotted time, but overall their performance was on par with participants working without stereoscopic glasses.

It was assumed that the early performance of the participants in the virtual tasks would depend in part on their previous exposure to 3D software, and those participants with previous experience of 3D modelling and GIS software would be more comfortable manipulating objects in 3D space from the beginning. This proved not to be the case, although results from other experiments in related fields suggest that a longer exposure to the virtual interface over a course of multiple sessions would improve the performance of participants in the reconstruction tasks(Keehner et al., 2006).

3D heatmaps reveal that the interactions of successful participants in perpendicular planes (in our experiments in planes parallel to the XY plane, see Figure 41) occur over a wider area than those of unsuccessful participants, while motion at different points on the Z-axis is less frequent. The interactions of unsuccessful participants exhibit a greater range of motion along the Z axis, with less overall motion in planes parallel to the X-Y plane. It is clear from this that successful participants make more use of the available X-Y screen space, with more activity occurring in the spaces between hotspots. In contrast, the unsuccessful participants have a much less energetic profile, with more separation in the Z axis. It is possible that the effect of perspective scaling is a contributing factor in the performance of these participants, with distant fragments being misinterpreted as smaller than they actually are.

In the course of the experiments, several behaviours were observed that could improve the virtual reconstruction process for cuneiform fragments. Firstly, it was observed that more successful participants kept fragments close to each other in the Z axis, and as such a visual representation of Z depth within the workspace may help to help participants to perform better. However, it was also observed that restoring depth perception by stereographic representation does not improve participant performance. It was noted that participants tended to begin with a larger fragment, with which they then try to match with smaller fragments. In a virtual system that automatically suggests possible matches, a bias toward suggesting smaller fragments than the one currently held may also improve the participant's performance. Other features that could improve the experience for participants working within a virtual system include the ability to glue multiple fragments together so that they can be manipulated as a single object, and the ability to magnify fragments so that close inspection of edges can be carried out quickly.

A system designed to maximize the advantages of the virtual environment whilst minimizing the inherent limitations could potentially open up the field of cuneiform reconstruction to new audiences, and free scholars from the drudgery of manual reconstruction. It is also likely that the research behind such a system would be applicable to a number of other fields within the archaeological community, such as fresco(Funkhouser et al., 2011) or potsherd reconstruction (Carvallo & Dunlop, 2001; Koutsoudis, Pavlidis, & Chamzas, 2010; Masayoshi et al., 2001).

6.3 The Effect of Virtual Tools on the Reconstruction Process

It is clear from later experiments that the tools designed to facilitate the reconstruction process have a significant, positive effect on the process of virtual fragment reconstruction. Not only does the frequency of interaction with the fragments increase when participants are using the tools, but the number of raw matches suggested by users increases by over 100%. This development contributes to a number of fields within the wider archaeological community, including all forms of organic and inorganic fragment reconstruction. In the wider community, the potential applications for these tools are diverse, including molecular visualisation, surgical preparation, and computer aided design.

While it was hoped that some level of performance prediction would be possible, the GEFT score of individuals did not have any obvious significant value as a predictor, although it did offer some insight into the participant's predisposition towards the interface. Participants with higher GEFT scores were more favourably inclined towards the virtual system. It is well recorded that a high cognitive load will increase the chance of errors occurring in a task, and will also increase the frequency of correspondence bias in group based tasks. Therefore, it is likely that participants with lower cognitive load will perform more effectively during reconstruction tasks.

It was interesting to observe that the participants overlaid their own systems of working onto the interface when a default system was not provided. In early experiments, participants were presented with fragments pre-loaded on screen in a random order. When faced with this situation, a large proportion of the users began by selecting the largest fragment from the set, and then selecting the next smallest fragment. In later experiments, the participants were required to load the fragments into the virtual environment by clicking on accurately scaled thumbnail images of the fragments. The thumbnails were presented in a horizontal list, positioned at the bottom of the screen. In this case, a large proportion of participants no longer began by selecting the largest fragment, but instead selected the left-most fragment and then proceeded to load all of the fragments moving from left to right. In the majority of cases, the order inherent within the interface overcame the participant's natural desire to impose order. Further investigation into this effect may reveal whether this observation can be used to cluster likely matching fragments near to each other, or whether cultural differences affect the order that users click.

6.4 Conclusions

The research outlined in this thesis has answered four principal research questions identified in section 1.3:

Is 3D capture and visualization a practical method for the preservation by recording of cuneiform fragments, and does the current state of technology support automatic or manual reconstruction in a meaningful way?

The technologies available for the preservation by recording of cuneiform are well developed, but there are numerous barriers and considerations to the uptake of these technologies. With respect to automatic reconstruction, expert oversight is still required to give final approval that two fragments match together, regardless of whether a match was generated by a crowd sourced system or by an agent based algorithm (see figure 49). In the case of human computed matches, an individual may be subject to unexpected biases, inexperience, or external distractions which cause them to suggest an incorrect match. For an agent based match, it has been repeatedly shown that false positives are a common problem when matching fragments. This dependence on the human element has already been discussed, and given that the likelihood of imperfect matching surfaces is high, it is unlikely that any system (human or machine based) will ever be able to perform effectively without the final endorsement of an expert. Humans and computers acting in tandem are likely to provide a more formidable and robust solution to the matching problem than just computers alone.

What strategies and behaviours are employed during fragment reconstruction tasks in the real and virtual world?

Experiment 5.1 revealed a number of strategies and behaviours adopted by participants. Although it is difficult to project the performance of an individual participant beforehand using their prior experience or the results of congnitive testing, it may be possible to make judgements based on their initial interaction strategies and performance over time. The experiment described in section 5.1 shows methods of interaction and behaviours of individual participants that can be used to predict their success at the reconstruction task, and in future work it may be possible to use these as an early predictor of confidence for suggested matches.

Can virtual tools be used to increase the level of interaction between users and fragments the virtual environment?

The experiment outlined in section 5.2 has clearly shown that the level of interaction between users and fragments can be increased by the application of specially designed tools that take into account the special nature of the reconstruction task. This result has broad implications for the process of virtual reconstruction, irrespective of the specific field.

Can virtual tools be used to increase the number of fragment joins that a user makes in the virtual environment?

The results of experiment 5.2 shows how the interaction tools developed subsequent to experiment 5.1 lead to a very significant increase in the amount of fragment joins made by participants using the system. Again, this result has potentially far-reaching benefits in for field of virtual fragment reconstruction, both inside and outside of the archaeological and heritage context.

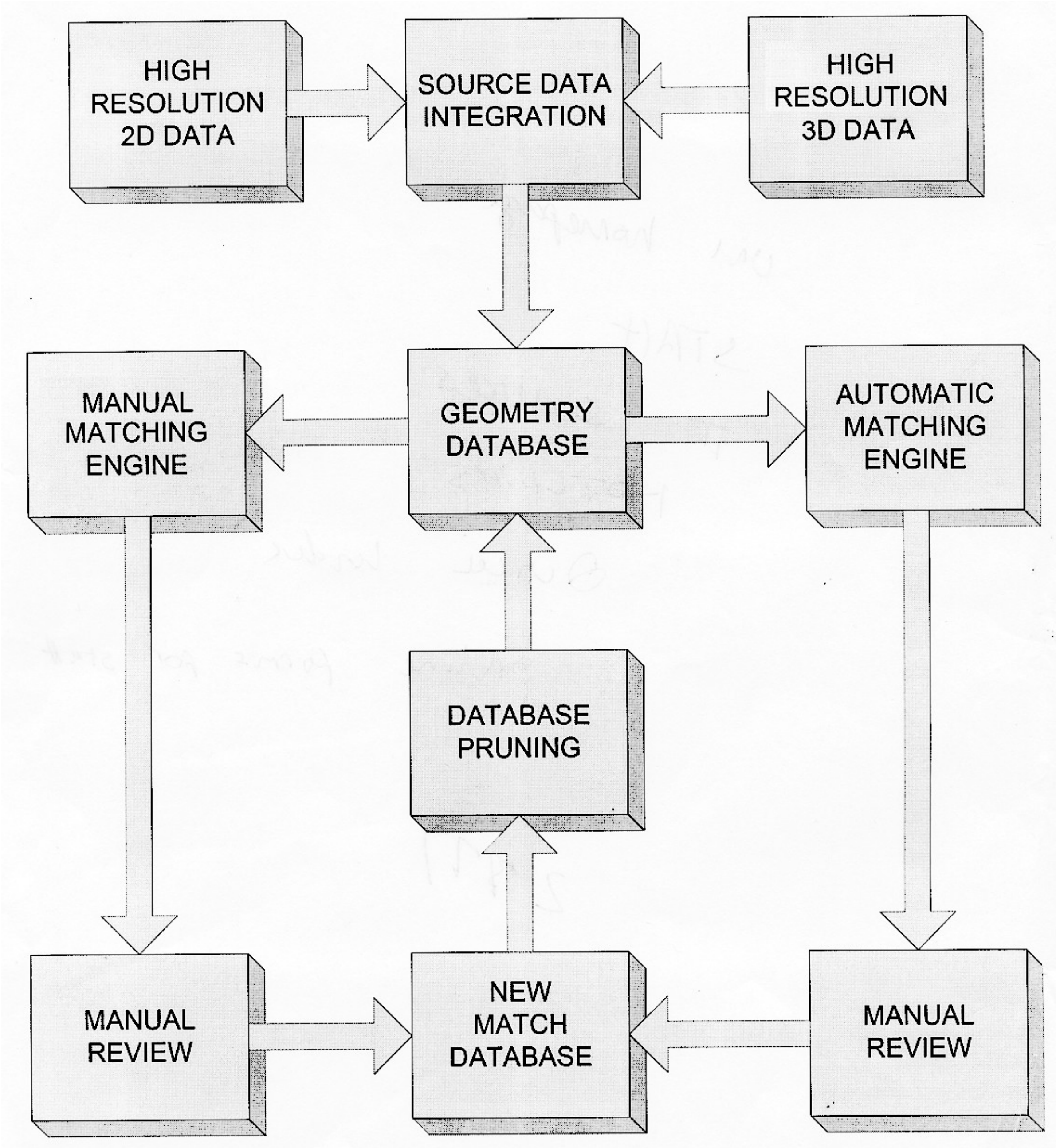


Figure 49: Figure showing the role of manual review in the automatic and manual matching of fragments from a variety of sources. Human curation of the database is necessary to maintain confidence in the accuracy of stored information.

The results of our experiments indicate that the manual reconstruction of fragments is faster than virtual reconstruction, and the reasons for this speed difference cannot be entirely mitigated by current technology. However, the physical world does not allow for easy parallel processing of fragment sets, nor does it permit casual accessibility to the non-expert. Therefore, despite the limitations of a virtual system, the potential for task parallelization and human computation makes virtual reconstruction an attractive choice for fragment joining. Once again, it is possible that the cost of maintenance and upkeep for a virtual reconstruction system may hinder its uptake. Storage and data transfer form only part of the overall cost of such a system, with constant maintenance required to keep the system running. The internet browser is not a stable platform, and during the development of the experimental system described here, it was necessary on several occasions to rewrite sections of code that had been rendered obsolete or inoperable by browser updates or API refactoring. The expertise to carry out these modifications must be made available throughout the life of any project that relies on a virtual system.

6.5 Further Work

The research described here has revealed behaviours and strategies used during the process of reconstruction, and has shown how custom tools can positively affect the reconstruction process. However, there is much scope for further work to refine the results described here, and to advance knowledge further.

With regard to the use of touchscreens over the standard keyboard and mouse, it was noted during experiment 2 (the analysis of virtual tools) that the TLX score for physical demand was very strongly related to the use of the touchscreen ($p = 0.00009$), yet the overall number of interactions performed by the participants during experiment four (the touchscreen task) did not vary significantly from those in task three (the interaction task). This effect is possibly due to the large size of the touchscreen used, and additional experiments with smaller tablets may confirm this is the case.

Additionally, it has been shown that the performance of users on virtual systems does not normalise for a period of several weeks, even where participants have prior knowledge of the task at hand (Keehner et al. 2006). It was impractical to undertake an experiment lasting for several weeks during this project, but it would be interesting and academically profitable to discover the effect of the virtual tools after several weeks of training, so that the participants have chance to normalise in their abilities. It is possible that when participants are allowed to reach a higher level of familiarity with the system, a significant and measurable correlation may emerge linking the participants success rate with their prior experience or cognitive style.

Time constraints prevented the individual testing of each virtual tool in isolation. It would also be wise to design a study to assess the effect of each virtual tool and each combination of virtual tools to find the most effective configuration for the reconstruction system's interface.

The research outlined in (Collins et al., 2014) indicates that further development into matching that considers presorting of fragments by different criteria could lead to a computationally lighter heuristic system for automatic matching. If this research is realised, then the potential for artificial agents to interact with the existing system using notes or stigmergic interaction could be realised, with user consensus moderating the validity of the results returned by agents by a system of up-voting and down-voting.

Further research into 3D printer design is also possible, with the expiry of several key patents (Hornick & Roland, 2003), modifications that improve the quality of FDM printing may be easily implemented. Specifically, the addition of a heated build chamber to equalize the temperature around the model during the build process and prevent excessive cooling could make the production of larger ABS prints reliable.

6.6 And Further Still

The following narration considers the combination of existing technologies with reference to the process of cuneiform reconstruction and visualisation:

> *Imagine walking up to something that looks like a touch table, and using it to browse information as we do today. Now imagine selecting an object from a list, and seeing it appear as a plain white physical object on the table a minute or so later.*
>
> *Pick up that object on the table, a cuneiform tablet for example, and a surface texture is projected onto it, so that it looks like the original object. You can touch the object, you can use it as part of an interface, or as an independent display object on the table. You could print a clipboard and pencil that you can pick up and move around on the table, while using it as an actual clipboard and pencil within the confines of the table. Or print a screen that you can show independent video windows on. Or print a copy of an artefact that you can show multiple surface textures on, so you can see what it would have looked like when it was new, and how it aged. When you're done with the object, you drop it into a slot at the side of the table, and it gets recycled into the next object.*
>
> *This probably sounds like science fiction, but the concepts here are not in the realms of Theodore Taylor's Santa Claus machine. The technology discussed here is well within the realms of capability. This is a combination of a wax based 3D printing technology, live projection mapping and gesture recognition. These are all technologies that exist now, and that we've worked with, or we have seen working. Imagine what this technology could mean in the museum context, or in the context of cuneiform reconstruction. I have spoken before about the need to find the 3D printing equivalent of the Amazon Kindle - this could be the first steps towards that. A machine that visualizes an object as an interface to data, completely, and temporarily, within the space of a touch table.*
>
> - Andrew Lewis

CHAPTER 7: REFERENCES

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APPENDICES

Appendix A: Python Code for Photogrammetry

```
def trim (im,thresh=250,mode="<"):
 from PIL import Image
 wid,hei = im.size
 matrix = im.load ()
 sil=[]
 x=y=0

 if mode=="<":
 while y<hei:
 while x<wid:
 (r,g,b) = matrix[x,y]
 if r < thresh:
 scan=x
 while scan < wid:
 (r,g,b) = matrix[scan,y]
 if g==255:
 sil.append ( (x,y))
 sil.append ( (scan-1,y))
 break
 scan+=1
 x+=1
 y+=1
 x=0

 xsil=[sil[i][0] for i in range (len (sil))]
 ysil=[sil[i][1] for i in range (len (sil))]
 imout=im.crop ( (min (xsil),min (ysil),max (xsil),max (ysil)))
 return imout

def findx (src, style="<", threshold=200):
 from PIL import Image
 bg = threshold+5
 par=[]
 wid,hei = src.size
 xcen = wid/2
 ycen = hei/2
 # need to include cropping so that image is minimum size before rotate and resize
 src=trim (src)
 tmp1 = src.rotate (45, expand=1)
 tmp2 = Image.new (src.mode, tmp1.size , (bg,bg,bg))
 tw,th = tmp2.size
 tmp2.paste (src, ( (tw-wid)/2, (th-hei)/2))
 src=tmp2

 wid,hei = src.size
 xcen = wid/2
 ycen = hei/2

 if style=="<":
 for a in range (360):
 im = src.rotate (a)
 matrix = im.load ()
 for x in range (1,wid):
 r,g,b = matrix[x,ycen]
 if g < threshold:
 par.append (xcen-x)
 break
 else:
 for a in range (360):
 im = src.rotate (a)
 matrix = im.load ()
 for x in range (1,wid):
 r,g,b = matrix[x,ycen]
 if g > threshold:
 par.append (xcen-x)
```

```
 break
 return par

def descale (iput):
 minimum = min (iput)
 oput =[]

 for item in iput:
 oput.append (item-minimum)
 return oput

from PIL import Image
src = Image.open ("z:\Brick.jpg")
print findx (src)
print descale (findx (src))
```

Appendix B: Post-Task Interview Transcriptions (Exp. 1)

47801 T1 F1

Do you think the tablet is complete?
No

Do you want to make any changes?
No

How do you think you did?
I don't know, I think I did alright because I don't think they are part of the same tablet, and I don't... I'm not sure where they would go. They might, but I don't think you could be sure.

Is there anything you would do differently if you were going to do the task again?
I might get something to stick them together, blutack or something, because it's quite difficult holding it.

Do you have any tips or tricks for people who might be doing this task in the future?
Maybe looking at the colors, because the colours are different. You think they should go together in terms of shape but if you actually look closely, these are different colors to those.

47801 T1N+2 F4
Do you think the tablet is complete?
There might be bits missing off that end.

Do you want to make any changes?
No.

How do you think you did?
I think I did alright.

Is there anything you would do differently if you were going to do the task again?
No

Do you have any tips or tricks for people who might be doing this task in the future?
Look for the colours and the insides, rather than the markings, because they do have marking on them, but the colors are more good.

47801 T2 F3

Do you think the tablet is complete?
No.

Do you want to make any changes?
No.
How do you think you did?
I didn't do very well on that one

Is there anything you would do differently if you were going to do the task again?
No

Do you have any tips or tricks for people who might be doing this task in the future?
No, Probably not.

47801 T2 2N F5

Do you think the tablet is complete?
No. I think that was several different tablets

Do you want to make any changes?
No.

How do you think you did?
Not brilliantly, unless they are all different tablets and I'm right on that.

Is there anything you would do differently if you were going to do the task again?
No

Do you have any tips or tricks for people who might be doing this task in the future?
No, Probably not.

47802 T1 F1

Do you think the tablet is complete?

Yes

Do you want to make any changes?

No

How do you think you did?

It went OK. I thought that two pieces weren't part of the tablet and I had them separate which kind of made them so I could see it kind of fitted if I turned it upside down.

Is there anything you would do differently if you were going to do the task again?

Get some foam so that you can place the tablets on the foam, because it's difficult to hold them in one hand, especially if it's falling apart and you want to put it down to pick something up. Or use sticky tape or something.

Do you have any tips or tricks for people who might be doing this task in the future?

Same as I said.

47802 T1N+2 F4

Do you think the tablet is complete?

The tablet itself is not complete, I couldn't fit these pieces anywhere.

Do you want to make any changes?

No

How do you think you did?

More difficult than the previous one. On the previous one I started off with a big piece but it was difficult to see anything fitting with the bigger piece.

Is there anything you would do differently if you were going to do the task again?

I wouldn't be as quick starting with the big pieces. Or maybe I would, I would probably still start with them.

Do you have any tips or tricks for people who might be doing this task in the future?

Put pieces that don't fit, or don't seem to fit anywhere out of the way.

47802 T2 F3

Do you think the tablet is complete?

I couldn't tell, I don't think so. I had no idea whether the pieces actually fit together.

Do you want to make any changes?

How do you think you did?

Not very well

Is there anything you would do differently if you were going to do the task again?

No.

Do you have any tips or tricks for people who might be doing this task in the future?

Yes – Get the real fragments. At some point I moved the fragments closer to the front, which made it easier to get a closer look, which made it a little bit easier to see whether they had similar marking on there and whether they fit better. It's difficult to see whether it matches, it's more an estimated guess in that it hopefully matches. If I looked from the side the fragment was still skewed and I had no idea why or how to accommodate for that.

47802 T2 2N F5

Do you think the tablet is complete?
I have no idea. I couldn't possibly match all the pieces and try to fit them.

Do you want to make any changes?
I would have liked to have made a complete one.

How do you think you did?
Not well.

Is there anything you would do differently if you were going to do the task again?
Get the real fragments.

Do you have any tips or tricks for people who might be doing this task in the future?
Run. Get the real fragments.

47803 T1 F1

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No – Without any paste/glue that's the best I can do.

How do you think you did?
Fine.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
It's sort of like with a jigsaw. Observe the surface layers on each side and give them a little bit of a compare and a bit of a feel then put them down together.

47803 T1N+2

Do you think the tablet is complete?
Yes
Do you want to make any changes?
No. I think it's terribly likely that those two pieces go together but the height feels wrong. For this it may fit but it there would be a piece needed to prove it.

How do you think you did?
I think I did alright.

Is there anything you would do differently if you were going to do the task again?
No

Do you have any tips or tricks for people who might be doing this task in the future?
Same as before.

47803 T2 F3

Do you think the tablet is complete?
Do you want to make any changes?

How do you think you did?
Terribly. I couldn't feel it. There's a physical click when the pieces go together. I could guess and I had a few guesses, but....

Is there anything you would do differently if you were going to do the task again?
No. I think as you used it you would get more used to the controls, but that would necessarily make it faster, because you're not using the tactile, weight, height, size issues that you do when you're holding them you have to rely more on color and shape and things, and I think that you would get better at that over time.

Do you have any tips or tricks for people who might be doing this task in the future?
Focus on the color and shape issues rather than the size, because that will help with the orientation, although that's very difficult with pottery because it can be very different within one vessel.

47803 T2 2N F5

Do you think the tablet is complete?
Do you want to make any changes?

How do you think you did?
Terrible.

Is there anything you would do differently if you were going to do the task again?
I think I should have used the space key turn thing and looked at the whole thing front and back together before moving the individual pieces.

Do you have any tips or tricks for people who might be doing this task in the future?
I would say that one because it's not what you think of doing, you think of looking at the bits on their own before you flip them.

47806 T1 F2

Do you think the tablet is complete?
Yes.

Do you want to make any changes?
No.

How do you think you did?
I solved the puzzle so I guess I did okay.

Is there anything you would do differently if you were going to do the task again?
I don't think so. No.

Do you have any tips or tricks for people who might be doing this task in the future?
I wouldn't give them any tips or tricks.

47806 T1 2N F4

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No

How do you think you did?
I don't know. It's hard to know because there is a piece missing, there is a clear chip, but from what I can tell it isn't any of the ones that is on the table.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
No.

47806 T2 F1

Do you think the tablet is complete?
No.
Do you want to make any changes?
No.

How do you think you did?
I failed the task, I know that. I didn't like the way of controlling the pieces, I felt it was so cumbersome that I was just waiting my time.

Is there anything you would do differently if you were going to do the task again?
Stop sooner.

Do you have any tips or tricks for people who might be doing this task in the future?

No.

47806 T2 F5

Do you think the tablet is complete?
No

Do you want to make any changes?
No

How do you think you did?
I wanted to stop because I got bored. One of the problems is that when you're doing this for real you can use both hands, and here you can only ever turn one and then the other, and it's really difficult because you cant see how it fits, and there's no way of knowing. You've got no perspective and it's just 2D. The color helps but what you need is something like haptic gloves.

Is there anything you would do differently if you were going to do the task again?
No

Do you have any tips or tricks for people who might be doing this task in the future?
No

47807 T1 F2

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No

How do you think you did?
It took me a long time – I thought they were two separate pieces and I was going through the whole thing about color and where the text was and those sorts of things and I assumed it was two different ones for quite some time, and then it was only at the last minute I realized so I could have twigged that earlier.

Is there anything you would do differently if you were going to do the task again?
I'd have started with the bigger pieces rather than trying to put the smaller pieces to the large pieces.

Do you have any tips or tricks for people who might be doing this task in the future?
I think the burning is key – the color- on these. Color is really useful.The actual text is not very useful until you get it right. You can't try and match the text, it's too fragmentary, and I'd go for the big pieces first.

47807 T1 F4

Do you think the tablet is complete?
It's not complete, but most of it is there.

Do you want to make any changes?
No.

How do you think you did?
This was a lot harder, partially it looks like -if I'm right- some parts have been burntafter they've been broken, so it's much more complicated, lots of the lessons I learned last time weren't applicable.

Is there anything you would do differently if you were going to do the task again?
Following the first one, the assumptions were different because part of the back is actually not the text, and some of it is with text, and you start bringing your own prior assumptions and they're wrong. I'm less certain about doing it now.

Do you have any tips or tricks for people who might be doing this task in the future?
Contrary to my last one I'd say don't rely on color, and don't rely on where text is because it can be anywhere.

47807 T2 F1

How do you think you did?
Not very well, that was really tricky and really good fun. It was an interesting experience and really useful for me. There were two pieces and two pieces that I think I got right but I was trying to bring them together because I think it is a single object, but I'm not 100%, I think it is. I don't think I did

brilliantly.

Is there anything you would do differently if you were going to do the task again?
Sorting out the rotate. I used the obvious functions first, and moving the camera enabling you to move within the plane was just fantastic, and also because the light changes obviously when you move the camera, and that was really tricky. The movement is useful when you're trying to find subtleties. I was finding that the text is less useful, but the shapes of the breakages and the way they had fractured was quite useful. Just being able to move the camera and bearing that in mind.

Do you have any tips or tricks for people who might be doing this task in the future?
Read the instructions and read them properly. Bear in mind that the whole thing is much more sophisticated piece of software than any of the 3D stuff I've used before. I was expecting (as I was expecting other people) to think that you can just rotate and that's where you are, but the idea of moving across planes and things, I've not come across it. I would say make sure you're aware of all the functionality.

47807 T2 F5

How do you think you did?
Not very well again. I certainly matched two pieces together, another two I'm not sure if it was two objects.

Is there anything you would do differently if you were going to do the task again?
I don't know, it's just really tricky.

Do you have any tips or tricks for people who might be doing this task in the future?
I think possibly I relied on color too much because it's got the texture on them, I'm relying on the texture too much, and I don't know whether I'm right. So that'd probably be the only thing I'd comment.

47808 T1 F2

Do you think the tablet is complete?
I'm confident that it isn't.

Do you want to make any changes?
No

How do you think you did?
I think I did okay.

Is there anything you would do differently if you were going to do the task again?
I wouldn't have bothered (because it's a test) trying to put that one in.

Do you have any tips or tricks for people who might be doing this task in the future?
Look at both sides.

47808 T1 2N F4

Do you think the tablet is complete?
I'm confident that it isn't. There's at least two bits missing.

Do you want to make any changes?
I'm not 100% positive that I've got it.

How do you think you did?
Well, less well than last time.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
Check all the bits that you've got left.

47808 T2 F1

How do you think you did?
Not very well.

Is there anything you would do differently if you were going to do the task again?
I would not look at the surface text, I'd look at the broken fracture surface. It was easier to match, but harder to find. The text is easier to look at, there are rows of text there but it's hard to see sometimes. Then I looked at the broken edges then I started to see bits that matched and curves that fit together.

Do you have any tips or tricks for people who might be doing this task in the future?
That you can scroll the mouse to zoom, and the camera pan from side to side. The bit where you can move the model in and out is z-relative to the model not where you are, but you can allow for that.

47808 T2 F5

How do you think you did?
Better. It's weird. On one hand I think I did better. At first I thought this is easier then it was almost disappointing, because there's that conflict between the fact you can see the colors and the textures so I feel I'm really seeing it, and the colors and textures got in the way of the shape. The gold one didn't have that, but I think overall I preferred it. I found it more frustrating, but I think it was more productive.

Is there anything you would do differently if you were going to do the task again?
I'd probably go slower. I lost time getting keys wrong and accidentally moving things I didn't mean to move. I had something nearly right but then I moved it out of the way when I meant to move the camera. And there's no undo so I couldn't undo that.

Do you have any tips or tricks for people who might be doing this task in the future?
Same. Use the camera view a lot. Zooming in and out helps. Don't be fooled by color.

47811 T1 F3

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No

How do you think you did?
Okay

Is there anything you would do differently if you were going to do the task again?
No

Do you have any tips or tricks for people who might be doing this task in the future?
I think the face first. Look at the top face of the tablet. That is the most important clue that you need to look at. And then the shape, you'd guess the size of the shape that would complete the missing fragments.

47811 T1 F4

Do you think the tablet is complete?
Yes, from what fragments I've got.

Do you want to make any changes?
Yes. Now it's complete.

How do you think you did?
I think I did okay.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
I think the same as before. The face and side of the tablet Give you a big clue how to assemble the fragments. Also the lines on the face are a big clue.

47811 T2 F2

How do you think you did?
Not very good at all.

Is there anything you would do differently if you were going to do the task again?
Yes, maybe. I think I need to see the pattern of the text clearly because I can't find the pattern quite clearly. I might need to zoom in a little bit more.

Do you have any tips or tricks for people who might be doing this task in the future?
I think you need to be as close as possible with a clear resolution, and the depth needs to be aligned. The size of the fragments, and the color of the fragments you could try to match.

47811 T2 N+2 F5

How do you think you did?
Better than the first one. I think because I learned the new method to see from a different angle. It's quite important to see around the fragments so you know the alignment is matched.

Is there anything you would do differently if you were going to do the task again?
I might do differently maybe, if the time is even more. I need more time to 3D look or realign the fragments because I need to be really familiar with the system before I move the fragments easily.

Do you have any tips or tricks for people who might be doing this task in the future?
Pattern of the face of the fragments, and the back face is also important. The shape of the tablet, the side of the fragments should be matched against the side of the tablet.

47812 T1 F3

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No

How do you think you did?
I think pretty well.

Is there anything you would do differently if you were going to do the task again?
Yes. The little piece has writing on, but I didn't see it at first.

Do you have any tips or tricks for people who might be doing this task in the future?
See if there is any writing on any of the pieces and then see how they fit together.

47812 T1 F4

Do you think the tablet is complete?
With the pieces I've got, yes.

Do you want to make any changes?
No.

How do you think you did?
Pretty well.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
Same as before.

47812 T2 F2

Do you think the tablet is complete?
No

Do you want to make any changes?
No

How do you think you did?
Pretty Badly. You can't really see if they fit together so it's hard to figure out if it works.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
Turn all of the pieces before you try to figure out if they fit together.

47812 T2 N+2 F5

How do you think you did?
Pretty badly. It took me 12 minutes if there are pieces that would fit together.

Is there anything you would do differently if you were going to do the task again?
Probably not.

Do you have any tips or tricks for people who might be doing this task in the future?
Writing and color says more than the image I think.

47804 T1 F1

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No, I don't think so. Maybe the back one, but no.

How do you think you did?
Reasonably well, it's in one piece.

Is there anything you would do differently if you were going to do the task again?
Use some glue.

Do you have any tips or tricks for people who might be doing this task in the future?
It's just like doing a jigsaw, start putting them together until they feel like they fit.

47804 T1 N+2 F4

Do you think the tablet is complete?
Ther's a couple of bits missing, but it's complete as far as the bits that I've got.

Do you want to make any changes?
No

How do you think you did?
Reasonably.

Is there anything you would do differently if you were going to do the task again?
Discard these bits earlier on.

Do you have any tips or tricks for people who might be doing this task in the future?
Discard these bits earlier on.

47804 T2 F3

How do you think you did?
Alright. I just couldn't get this piece to fit.

Is there anything you would do differently if you were going to do the task again?
Start on the back. Follow the colors rather than the shape.

Do you have any tips or tricks for people who might be doing this task in the future?
Follow the colors rather than the shape.

47807 T2 2N F5

How do you think you did?
Not brilliantly. I think there must be two tablets, I'm not even sure that what I've got there is right.

Is there anything you would do differently if you were going to do the task again?
Realize that there's two tablets earlier and try and separate them, or not if there's just one tablet.

Do you have any tips or tricks for people who might be doing this task in the future?
Same again.

47809 T1 F2

Do you think the tablet is complete?
Yes

Do you want to make any changes?
Yes

How do you think you did?
I think this one's gone together, I've just realized that these may be two sided, so I maybe needed to check the other one.

Is there anything you would do differently if you were going to do the task again?
Yes, I'd have checked both sides.

Do you have any tips or tricks for people who might be doing this task in the future?
Color matching, lines. There's two tips to start that way.

47809 T1 2N

Do you think the tablet is complete?
Yes

Do you want to make any changes?
No

How do you think you did?
I think there could be more parts of it. The contours are fitting well, but there is a bit missing here that it would be nice to have, and there's a hole in it. I can't work out if they're in these parts. I think some of the colors on this has changed. I was trying to do it by color before, now I'm thinking that maybe parts can change color and so trying to match contours first might be better than colors. Colors is a good initial sort, but now I think it might be an error.

Is there anything you would do differently if you were going to do the task again?
Match close colors first, then match by contours.

Do you have any tips or tricks for people who might be doing this task in the future?
Colors first and follow contours. Maybe glue it together to hold it easier.

47809 T2 F1

How do you think you did?
Badly. They were all the same color, which didn't help because I was using that in my last search. Also sometimes I wanted to pick a direction or something to rotate and see how it looked in that direction and I wasn't sure how to get it that way. I may have forgotten the keypresses or the mouse presses sometimes. I think sometimes the key presses didn't work or it hit a rotation and wouldn't keep going the way I wanted it would just stop.

Is there anything you would do differently if you were going to do the task again?
Yes I made the mistake of getting a few pieces together, then I thought I'll see what that piece looks like there, so I took them apart which was a mistake because it took longer to put them back together. If I had a place to number them or save that, try something else and go back, then it would

have helped me.

Do you have any tips or tricks for people who might be doing this task in the future?
Read the instructions, and focus on the screen.

47809 T2 F5

How do you think you did?
A lot better. The colors helped me pick out surface details better. I didn't like the colors on the last one, but this one really helped me. It was a lot better the second time, it was an easier task.

Is there anything you would do differently if you were going to do the task again?
Yes. Not move so many things in and out of the plane to zoom them. I pushed things back and forwards then I was trying to fit them and I realized they were further back than I thought.

Do you have any tips or tricks for people who might be doing this task in the future?
Nothing different from what I've said. Just remember all the controls. Make sure you know all of them.

47813 T1 F3

Do you think the tablet is complete?
Yes
Do you want to make any changes?
No

How do you think you did?
Badly, probably. I haven't got fiddly enough fingers.

Is there anything you would do differently if you were going to do the task again?
No.

Do you have any tips or tricks for people who might be doing this task in the future?
Not really. Have a good look at it.

47813 T1 F4
Do you think the tablet is complete?
Well it looks like it goes together, but there's a gap so it's evidently not, but that's my shot at it.

Do you want to make any changes?
No

How do you think you did?
Badly again.

Is there anything you would do differently if you were going to do the task again?
No, I don't know what I could do differently.

Do you have any tips or tricks for people who might be doing this task in the future?
No.

47813 T2 F2
How do you think you did?
Horrendously. That was horrible.

Is there anything you would do differently if you were going to do the task again?
No, it was just tricky to use. Possibly because I'm a bit dense when it comes to this sort of thing.

Do you have any tips or tricks for people who might be doing this task in the future?
Have a good look at the instructions before you have a go at it.

47813 T2 N+2 F5
<<VIDEO RECORDING FAIL>>
How do you think you did?
N/A
Is there anything you would do differently if you were going to do the task again?
N/A
Do you have any tips or tricks for people who might be doing this task in the future?
N/A

Appendix C: Participatory Design Summary

This summary was produced by Eugene Ch'ng, Woolley S, Hernandez Munoz L, *et. al.* as part of the experiments outlined in the paper "The Development of a Collaborative Virtual Environment for 3D Reconstruction of Cuneiform Tablets" (Ch'ng et al., 2014). It is included because it was used to guide the design of the interface along with the results of the interviews and observations from the first experiment.

Participatory design session

We carried out a one-hour design session to produce user requirements and a paper prototype of a cuneiform virtual environment. Five people were involved in a brainstorming and a design exercise. Three expert software developers (one acted as a facilitator), one cuneiform scholar and one potential user without cuneiform experience. We used PICTIVE (Plastic Interface for Collaborative Technology Initiatives through Video Exploration) participatory design technique (Muller, 1991), where participants used non-computer representations of system functionalities (e.g. flipcharts, colour pencil, post-its, etc.) in order to encourage user participation to sketch a paper prototype of a virtual environment that may support the collaboration of cuneiform tablet reconstruction. Video recording was used to analyse the session and to produce design documents. The session began with an explanation of the aims and the methodology. We proceeded with a brainstorming exercise using the low-tech objects where each participant was able to contribute. The virtual environment was designed based on two scenarios, a potential user assembling fragments individually and a potential user working in collaboration with other people.

Scenario 1: Individual user interface.

Imagine you are comfortable sit down in front of your desktop or laptop and want to assemble a group of fragments that may belong to one or several cuneiform tablets. Please design the menus and functionalities that would do your task more efficiently and more enjoyable. For example, how the user interface would look like, the ability to see the fragments in a particular way, rotation, drag and drop, note taking, change colours when holding the fragment, etc.

Scenario 1: Individual user interface.

Imagine you are comfortable sit down in front of your desktop or laptop and want to start assembling a set of fragments that may belong to one or several cuneiform tablets. This time you can collaborate with other people to assemble them. Please imagine the types of notes, messages or annotations you could use to establish a two way communication system with others, as well as the menus and functionalities that would do your task more efficiently and more enjoyable.

Potential users were advised to think through what they would like the system to do for them. Be concrete and specific. Be prepared to go through the steps that would be required to 'do the job'. They were remembered they were 'The Expert' on the content of the job, and they will contribute their unique knowledge and expertise to the cooperative design session. But they will not be surprised if their ideas change during the session.

Developers were advised that they should base their development of the system on discussions with the user, construct an initial or preliminary set of 'system components' that the users will manipulate (and change!) while exploring the task scenario. They were advised to be concrete and specific, not invest much ego in the specifics, as it was highly probable that they will change as the collaboration progressed. They were remembered, they were 'The Expert' on the system and its environment, and they will contribute their unique knowledge and expertise to the cooperative design session.

Results of the participatory design session

Participants started drawing 3D fragments in a flip chart that represented the user screen. The first question to arise was how to link fragments together trying to emulate what it is done physically. Participants agreed that there should be a "link/unlink button" to join or separate multiple fragments, this can be done using the right or the left button of the mouse. A toolbar should be put at the top of the screen to keep a standard user interface used in other programs such as Microsoft word. Icons and text menus were suggested to be implemented including link and unlink, fragment lay flat, reset (undo action), save session and print screen. A panel on the left side of the screen should be implemented to show information about the fragments (e.g., memos, tags and edge recognition tools). Fig. 1. shows the evolution of the paper prototype, from start to finish.

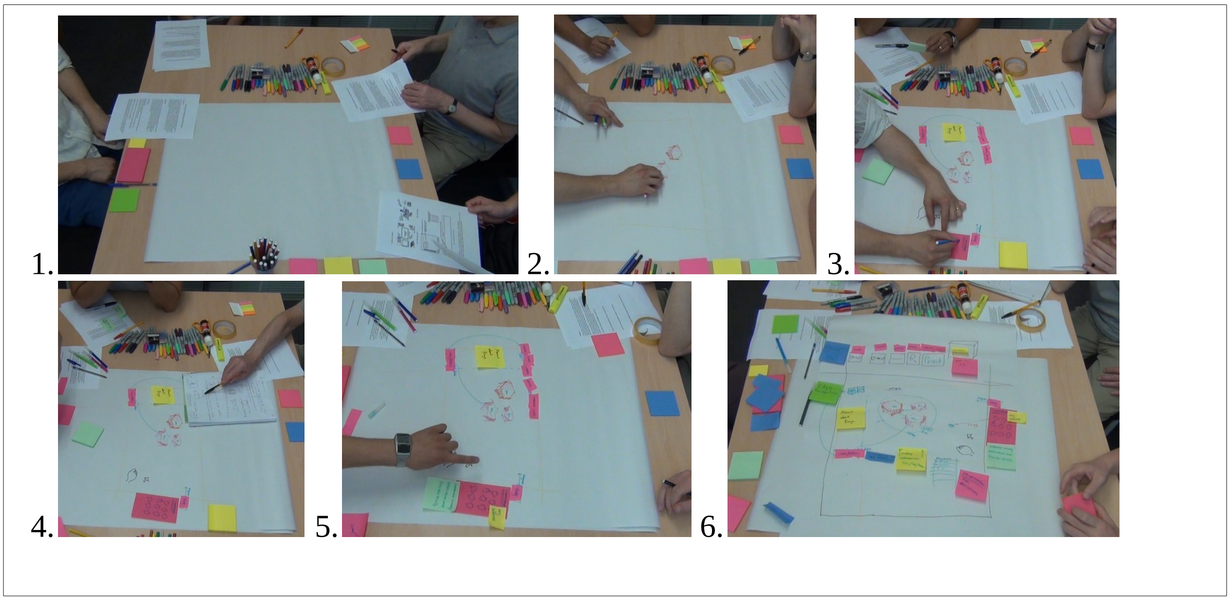

Fig. 1 Evolution of the paper-prototype through the session.

Another panel was suggested on the right side of the user interface to drag and drop new pieces to the centre of the screen. This panel should be able to organise the fragments by categories and be retractile. This panel would help the user to work in a set of fragments from a certain location, age and content. Our cuneiform scholar expert mentioned that the colour of the fragments was not important in real scenarios for their categorisation. He explained that the actual museum categorisation approach can be used. Museums categorise fragments by the location of their content: Averse and reverse, top and bottom edge, right and left edge, four corners, and piece from the middle. Museums use letters or numbers for every categorisation (e.g., K for piece from the middle, E for left edge and A for averse). The museum can be also part of the categorisation (e.g., BM for British Museum plus a number). Museums usually document the tablet thickness, width and length. Other categorisations in the virtual environment may include shapes, sizes and thickness, fragment content and script height. For example, credit documents (usually in landscape orientation), letters or astrological documents. Joints can be documented based on likely matches.

For example, clear joints of corner pieces. Our cuneiform scholar expert suggested that the computer could check possible joints rotating the fragments by one or two degrees up to 360 degrees over the x and y axis and suggest a percentage of chance that those fragments joins together. He suggested using polar coordinates to have two degrees of freedom for the angles and another degree of freedom for the radius (represented by the length of the fragment). Other types of joints include exacts (no fragments missing) and possible joints. As there are archives located in different places and every museum has a catalogue of the fragments, when they were written and the subject, it was suggested to assemble fragments of one collection and later find possible matches with other collections. Theses categorisations are a key point of the virtual environment. However, there is the challenge that not many people publish archives because every scholar is engaged with their own collection.

Table 1 shows the functionalities, menus, buttons, options, and events suggested implementing in a cuneiform virtual environment according to the participants' ideas.

Table 1. User requirements collected in the session

Functionalities	-Select a fragment -Mouse or a touchscreen may be used -Have simple and standard toolbars -Take into account the way fragments are classified in museums (fragment size and content) and how they are assembled. -Categorise fragments (e.g., using a taxonomy), based on content, size, orientation, collection, location. -Have support and moderation from cuneiform scholars. -Do a prioritisation of fragments that may be checked in the museum with the actual pieces. **Advanced functionalities (Optional):** -3D stereo vision -Edge recognition -Expert moderation -Have memos about fragments -Script recognition
Menus	-Toolbar icons should appear preferably at the top of the screen. -A categorisation collapsible panel should appear on the right side of the screen. -A panel for fragments information should appear on the left side of the screen -A panel for expert moderation and notes left from other people (cooperative work) should appear at the bottom of the screen.
Buttons	-Link and unlink fragments -Save session -Print screen -Lay flat (fragment) -Reset assembly (undo)

Because trying to join pieces together without tactile feedback appear to be very challenging, a good categorisation system would be essential (e.g., using a taxonomy). It should be one of the key features of the virtual environment. Furthermore, participants wanted that from the categorisation panel the user can drag and drop fragments to the centre of the screen to check manually (and optionally automatically) for possible matches of fragments that had been found in the same location.

Participants suggested two ways of finding and corroboration matches. First, the computer suggests matches from the categorisation panel; the user confirms them and indicates the museum to verify the match. Second, the computer categorises, filters and suggest matches of fragments (e.g., in clusters), the user manipulates and suggests matches, and an expert scholar moderates the session and indicate agreement, disagreement or indecision about the join and the need to indicate the museum to verify the matches. This would encourage a computer assisted collaboration work.

In order to implement those functionalities, a ranking based on “number of expert scholar likes” and a prioritisation list should be developed in a bottom panel. This panel also should have fragment information (info and status), expert moderation feedback (yes/no/maybe) and notes left from other people working in the same set of fragments. Fig. 2 illustrates the user interface suggested in our participatory design session.

Fig. 2 Final picture of the paper prototype. It can be seen a top toolbar and a right, left and bottom panels containing the features and functionalities of the virtual environment.

Optional functionalities suggested in the session, which may require advance processing algorithms include 3D visualisation to support users assemble fragments in less time. Automatic interpretation of tablet size, handwriting recognition, fragment location in the tablet, and edges recognition. Participants suggested that for collaboration with other people the bottom panel should have a space for notes left from others.